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Synergistic effects of sowing date and potassium nutrition on combating heat stress in wheat

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Abstract

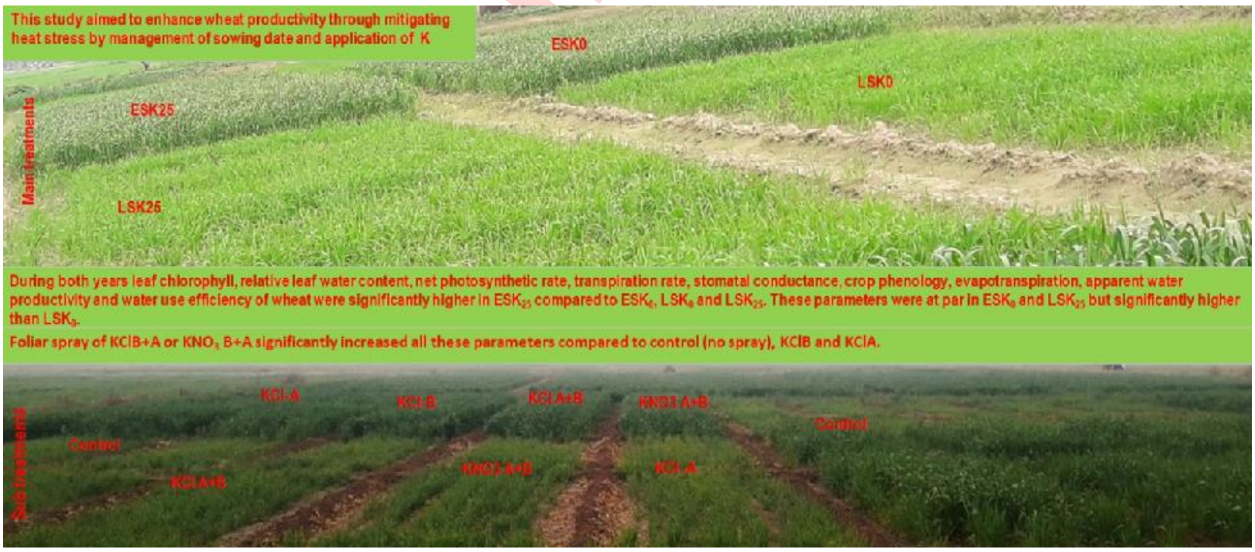
Aim: This study aimed to enhance wheat productivity under heat stress by management of sowing date and application of potassium.

Methodology: Field experiment in split plot design was conducted to study interactive effects of two sowing dates (early sowing (ES) on 30th October and late sowing (LS) on 30th November) and two soil K rates (no K (K_0) and 25 kg K ha^{-1} (K_{25}) in main plots and five foliar K sprays (control, 2 % KCl at booting (KCl-B) and anthesis (KCl-A), booting + anthesis (KCl A+B) and 2% KNO3 at booting + anthesis (KNO_3 A+B) in subplots to mitigate heat stress in wheat.

Results: Relative leaf water, chlorophyll content, evapotranspiration, apparent water productivity and water use efficiency of wheat were significantly increased by 25.1, 23.2, 22.9, 23.3 and 17.6 per cent, respectively, with ESK_{25} compared to LSK_0. Physiological traits increased while proline content decreased significantly with ESK_{25}. However, these parameters were at par in ESK_0 and LSK_{25}, but significantly different than LSK_0. Foliar spray of KClB+A or KNO_3 B+A significantly increased these parameters compared to control. Grain yield of wheat was significantly and positively correlated with all these parameters, except proline content.

Interpretation: The study confirms that early sowing, soil application and foliar feeding of K protects wheat from heat stress.

Key words: Heat stress, Potassium management, Sowing date, Synergism, Wheat



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Introduction

Wheat (*Triticum aestivum* L.), the most widely cultivated cereal crop, is the largest contributor with nearly 30% of the world grain production and 50 % of the world grain trade. According to FAO estimates, 198 million more tons of wheat will be needed globally by 2050, for a total production of 840 million tons. To meet this requirement, wheat production in developing nations would need to rise by 77 % (Sharma *et al.,* 2015). A number of biotic and abiotic stresses affect wheat production, making it more difficult to meet these production targets. Among these stress, the frequency of heat events during the reproductive growth periods of wheat have significantly increased due to global climate change which reduce wheat yield (Ullah *et al.,* 2020, Collins *et al.,* 2022). Heat stress in wheat generally occurs when temperatures exceed 30–35°C during sensitive developmental stages such as anthesis and grain filling. High temperature stress shortens crop duration, accelerates senescence, and reduces grain filling duration, ultimately leading to lower grain weight and yield. Studies have reported that even a 1°C increase in temperature can substantially reduce wheat productivity in many wheat-growing regions (Gyawali *et al.,* 2021).

In Asia, 10–50% of wheat yield reduction has been observed with 3–4 ^{0}C rise in temperature over optimum at grain filling stage (Hussain *et al.,* 2018). Short episodes of heat during early to mid-grain filling stages of wheat have negative effect on cell biochemistry, physiology and overall grain yield (Kumar *et al.,* 2014; Ullah and Chenu, 2019; Shenoda *et al.,* 2021), which could decrease up to 25% wheat yield in India. In the Northern parts of India, wheat sowing is delayed due to late harvesting of long duration rice varieties which results high temperature stress in wheat during post-anthesis period. Severe temperature stress in late sowing shortens the heading and maturity duration, which ultimately affects final yield and grain quality of wheat (Hakim *et al.,* 2012). To minimize the adverse effects of heat stress, several agronomic approaches like adjustment of sowing time, nutrient management and foliar application of protective compounds have been reported in earlier studies (Lakhani *et al.,* 2025).

Date of sowing has a direct relation with growth, yield attributes and yield of wheat which can be manipulated to counter the adverse effects of abiotic stresses. Therefore, early sowing immediately after rice harvest can be a viable option for protecting wheat from hot and desiccating climate during grain filling period (Kajla *et al.,* 2015; Paudel *et al.,* 2023). The negative impact of heat stress on wheat growth can also be reduced by soil application (Abro *et al.,* 2022) and foliar spray of potassium at different growth stages (Shahid *et al.,* 2020). However, most of the earlier studies have evaluated potassium application or sowing time independently under heat stress conditions. Despite these advancements, there is limited and fragmented information available from the last four years regarding the combined (integrated) effect of sowing dates along with soil and foliar potassium application on wheat performance under terminal heat stress, particularly under field conditions of the Indo-Gangetic Plains. Existing studies largely focus on single-factor interventions and do not adequately address the interaction between crop phenology (sowing time) and nutrient-mediated stress mitigation. Therefore, the present study was conducted with the aim to assess the integrated effect of sowing dates, soil and foliar potassium application on alleviating heat stress in wheat during the *rabi* season of 2021-22 and 2022-23.

Materials and Methods

Study area and experimental design: Field experiment was conducted in a split plot design with three replications during the *rabi* season of 2021-22 and 2022-23 at the Research Farm, Department of Soil Science, Punjab Agricultural University, Ludhiana. Combination of two sowing dates (early sowing (ES) on 30th October and late sowing (LS) on 30th November) and two soil potassium application rates (no soil K (K_0) and 25 kg K ha^{-1} (K_{25}) were kept in main plots and five foliar K sprays (control, 2 % KCl at booting (KCl-B) and anthesis (KCl-A), 2% KCl at booting + anthesis (KCl A+B) and 2% KNO_3 at booting and anthesis stage (KNO_3 A+B) were kept in subplots.

The weather data recorded during 2021-22 and 2022-23 rabi season showed considerable variation among different meteorological parameters throughout the cropping season (Fig. 1). The maximum temperature during 2021-22 cropping season was lower (15.7 ^{0}C) than long term normal (18.0 ^{0}C) during the month of January but higher in March (30.9 ^{0}C) and April (39.1 ^{0}C) than long term normal temperature of 26.7 and 34.7 ^{0}C in March and April. The maximum temperature during 2022-23 cropping season was lower in November (20.2 ^{0}C) than long term normal (26.6 ^{0}C), January (16.6 ^{0}C) than long term normal (18.0 ^{0}C) and April (32.9 ^{0}C) than long term normal (34.7 ^{0}C), but higher in February (24.8 ^{0}C) and March (27.8 ^{0}C) than normal temperature of 21.2 and 26.7 ^{0}C in February and March, respectively. The minimum temperature was higher in the month of January (8.4 ^{0}C), February (8.6 ^{0}C), March (15.9 ^{0}C) and April (20.5 ^{0}C) than their respective monthly normal temperatures of 6.0, 7.9, 12.0 and 17.5 ^{0}C during 2021-22. During 2022-23, the minimum temperature was higher in the month of December (7.7 ^{0}C), January (6.7 ^{0}C), February (10.4 ^{0}C) and March (14.8 0C) than their respective monthly normal temperatures of 6.6, 6.0, 7.9 and 12.0 ^{0}C.

During 2021-22, the cumulative pan evaporation was 341.3 and 286.5 mm on 30th October and 30th November sown wheat whereas cumulative rainfall was same (157.7 mm) for both dates of sowing. During 2022-23, the cumulative pan evaporation was 384.2.3 and 330.6 mm on 30th October and 30th November sown wheat whereas cumulative rainfall was same (106.7 mm) for both dates of sowing. The rainfall was same for two dates because there was no rainfall in the month of November during both years. The experimental soil (0-15 cm depth) was sandy loam in texture with 1.52 g cm^{-3} soil bulk density, 7.6 soil pH, 0.42 dS m^{-1} soil EC, 4.35 g kg^{-1} soil organic carbon, 325 kg ha^{-1} soil nitrogen, 23.3 kg ha^{-1} soil phosphorus, 157 kg ha^{-1} soil potassium, 2.8 mg kg^{-1} zinc, 15.3 mg kg^{-1} iron, 1.23 mg kg^{-1} copper and 11.8

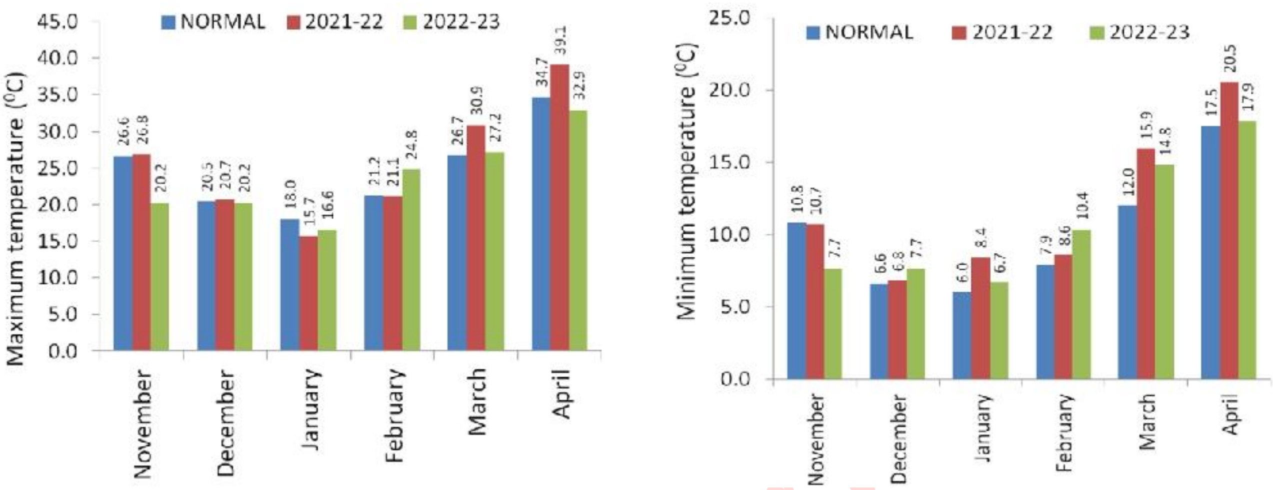

Fig. 1: Weather parameters compared to long term average (normal) during wheat seasons.

mg kg^{-1} manganese. Profile (0-100 cm depth) soil moisture storage at field capacity and permanent wilting point was 25.7 and 10.3 cm, respectively.

Agronomics practices: The primary and secondary tillage operations were done with tractor drawn disc harrow and cultivator before pre-sowing irrigation. A heavy pre-sowing irrigation (10 cm) was applied by dividing the field into smaller plots to ensure adequate moisture in the soil profile for germination. After the field attained proper moisture condition (field capacity), a fine seed-bed was prepared by giving two cultivations with cultivators each followed by planking to bring the soil to a proper tilth. Nitrogen and phosphorus were applied @ 125 kg N and 65 kg P_2O_5 ha^{-1} in the form of urea and diammonium phosphate. Full phosphorus was drilled with seed cum fertilizer drill in all plots at the time of sowing.

Treatment wise full potash (30 kg K_2O ha^{-1}) was applied as basal through muriate of potash. Half of the nitrogen was applied 2 days before first irrigation and the remaining half nitrogen was applied 2 days before second irrigation. Seed was treated with Gaucho 600 FS (*imidacloprid*) @ 4.0 ml kg^{-1} seed and Bavistan (*carbendazim*) @ 3g kg^{-1} seed before planting for protection against termite and fungal diseases, respectively. Sowing was done with seed cum fertilizer drill using seed rate of 100 kg ha^{-1} of PBW 824 wheat variety. The sowing was done on different dates for different seasons. The row to row spacing was kept at 20 cm with seed cum fertilizer drill. A post emergence application of Topic 15 WP (*clodinafop*) @ 400 g ha^{-1} for control of grassy weeds along with Algrip 20 WP (*metsulfuron*) for control of broad-leaf weeds was done after 30-35 days of sowing. The post-sowing irrigations were applied as per the irrigation schedule recommended by PAU, Ludhiana for wheat (Prihar *et al.,* 1974). Each irrigation depth was 75 mm according to measurements made from parshall flume. The crop was sprayed with Tilt 25 EC (*propiconazole*) @ 500 ml ha^{-1} at heading stage to control yellow rust and Rogor 30 EC (*dimethoate*) @ 375 ml ha^{-1} for control of aphids at heading and milking stage. Harvesting was done manually on different dates (depending upon the physiological maturity) with the help of sickles. Post-harvest, the bundles were made from the net area of each plot and tagging was done. The bundles were left in the field for sun-drying. Before threshing, bundle weight representing total above ground plant biomass was recorded for each plot.

Relative leaf water content: The relative water content of leaf samples was taken at the anthesis and milking stages. After taking the fresh weight of the leaf samples, these were kept in distilled water for 24 hr to obtain turgid weight, thereafter, the leaf samples were kept in oven at 60°C till a constant weight was attained to measure dry weight. The relative leaf water content (RLWC) was then calculated as per the formula given by Barrs and Weatherley (1962).

Chlorophyll content: The chlorophyll content (mg m^{-2}) was measured at anthesis and milking stages from fully expanded flag leaves using chlorophyll meter (SPAD-502, Spectrum Technologies, Plainfield, IL, USA). The data was measured from five flag leaves per plot and their average readings were taken.

Proline content: Proline content (mg g^{-1} sample weight) in leaves and grains of wheat was determined using acid ninhydrin reagent as per the method described by Bates *et al.* (1973).

Physiological traits: Gas exchange parameters including net photosynthesis rate (NPR), transpiration rate (TR) and stomatal conductance (SC) were determined at anthesis and milking stages from penultimate and flag leaf at 1 p.m. to 3 p.m. on clear day by using Infra-Red Gas Analyzer (IRGA, Model LCA-4).

Wheat phenology: Days to maximum tillering, booting, heading, anthesis/flowering, milking, dough, physiological maturity and harvesting stage were calculated as the day on which 80% plants had completed tillering, 50% tillers showed swollen base of the flag leaf, 50% ears emerged out of boots, anthers appeared from 50% of the ears, when milk like white liquid aged from spikelets, milk started to solidify in 80% of spikelets, hard yellow grains with 30-50% moisture and hardy yellow dry grains were formed.

Soil water balance components: Soil samples from 0-15, 15-30, 30-60 and 60 to 100 cm depths were drawn with screw auger and put in the aluminum moistures boxes for estimating the soil moisture gravimetrically. The moist soil samples were oven dried at 105 ^{0}C after measuring the fresh weight (FW). The dry weight (DW) of the soil samples was recorded after oven drying at 105 ^{0}C for 24 hr or till a constant weight was obtained. The percent soil moisture was calculated. Soil moisture storage (in mm) was calculated by multiplying the soil moisture fraction with soil bulk density (g cm^{-3}) and soil depth (mm). Total soil moisture storage (mm) was calculated by adding soil moisture storage of all layers. The following water balance equation was used to estimate changes in soil water storage (ΔS) as:

$$\pm \Delta S = I + R - ETa - D - R$$

Where, I is the irrigation, R is the rainfall, ETa is the actual crop evapotranspiration, D is the deep drainage and R is the surface runoff. Actual crop evapotranspiration (ETa) was estimated as the product of potential evapotranspiration (ET_0) and crop coefficient (Kc) values (ETa = ET_0 x Kc) as given by Allen *et al.* (1998). The ET_0, was estimated with CROPWAT 8.0 based on daily weather parameters (maximum and minimum temperature, mean relative humidity, wind speed, sunshine hours) obtained from the PAU Meteorological Observatory located near the experimental site. The locally calibrated crop coefficients (Kingra *et al.,* 2004) for different treatments in wheat were used to calculate ETa. Irrigation water applied (mm) was measured with Parshall flume, rainfall (mm) was measured with rain gauge at the experimental site. ΔS was determined by comparing soil moisture storage at sowing time with that at harvest time. Runoff was totally avoided due to the presence of sufficient high dikes of 20 cm. Deep drainage was measured by assessing the periodic soil moisture content in the soil profile (0–100 cm soil depth) and comparing it to the field capacity, *i.e.,* upper limit of water holding. Deep drainage was considered zero when soil profile moisture storage was below the field capacity, and calculated as the difference between field capacity storage and soil moisture storage plus irrigation/rainfall when soil moisture exceeded field capacity.

Apparent water productivity: The apparent water productivity (AWP) of wheat was calculated as the ratio between grain yield produced to the irrigation water applied (I) during the entire growing season (Rodrigues and Pereira, 2009).

Water use efficiency: The water use efficiency (WUE) of wheat was calculated based on the ETa and the amount of water supplied by irrigation (I) and precipitation (P) as per Perry *et al.*, (2009).

Statistical analyses: Data generated in different treatments statistically analyzed by ANOVA using a split plot design (Gomez and Gomez, 1984) and SPSS (Version 11) was employed for statistical analyses of critical differences among the means. Pearson correlation analysis was applied in order to find possible correlations between different parameters. In all the analyses, significance was accepted at a probability level of <0.05.

Results and Discussion

During both years, ESK_{25} significantly increased the relative leaf water content (RLWC) of wheat compared to ESK_0, LSK_0 and LSK_{25} after anthesis and at milking stage of wheat (Fig. 2). During both years, RLWC after anthesis and at milking was at par in ESK_0 and LSK_{25}, but significantly higher than LSK_0. Pooled analysis showed that RLWC increased by 25.1, 18.5 and 14.6 per cent with ESK_{25}, LSK_{25} and ESK_0 over LSK_0 respectively. Lotfi *et al.* (2022) also observed that application of 150 kg ha^{-1} K_2SO_4 increased the relative leaf water content of winter wheat by boosting osmotic adjustments, which maintains cellular turgor. During both years, RLWC after anthesis and at milking was significantly increased with foliar spray of 2% KCl at booting and anthesis (KCl B+A) or KNO_3 at booting and anthesis (KNO_3 B+A) than control (no spray), KClB or KClA. Pooled analysis showed that RLWC was increased by 10.6, 10.3, 6.1 and 4.1 per cent with KCl-B+A, KNO3 B+A, KCl B and KCl A, respectively, over control. One spray of KCl at booting (KCl B) or anthesis (KCl A) were at par for RLWC during both years at anthesis and milking of wheat, but significantly higher than control. However, KCl B+A and KNO3 B+A were at par with each other for RLWC during both years at both crop growth stages. Increase in RLWC with foliar spray of potassium may be due to stomatal regulation and enhanced water movement through xylem (Ali *et al.,* 2022).

During both the years, ESK_{25} significantly increased the chlorophyll content of wheat after anthesis and at milking stage (Fig. 3) compared to ESK_0, LSK_0 and LSK_{25}. Pooled analysis showed that chlorophyll content was increased by 23.2, 9.8 and 14.4 per cent with ESK_{25}, LSK_{25} and ESK_0 over LSK_0, respectively. During both years, chlorophyll content after anthesis and at milking was at par in ESK_0 and LSK_{25}, but significantly higher than LSK_0 which may be due to the application of K to soil that increased the nitrogen uptake and subsequently enhanced the chlorophyll content in wheat leaves (Ali *et al.,* 2019). During both the years, the chlorophyll content after anthesis and milking was significantly increased with foliar spray of 2% KCl (KCl B+A) or KNO_3B+A than control (no spray), KCl B and KCl A. Pooled analysis showed that the chlorophyll content was increased by 30.9, 34.7, 9.7 and 14.9 per cent with KCl-B+A, KNO_3 B+A, KCl B and KCl A, respectively, over control. However, KCl B+A and KNO_3 B+A at booting and anthesis were at par with each other for chlorophyll content during both the years at both crop growth stages. Sarwar *et al.* (2022) also found that 2% foliar K significantly increased the leaf chlorophyll under heat stress. The increase in flag leaf chlorophyll content with foliar application of potassium may be due to enhanced nitrogen uptake (Tanin *et al.,* 2023).

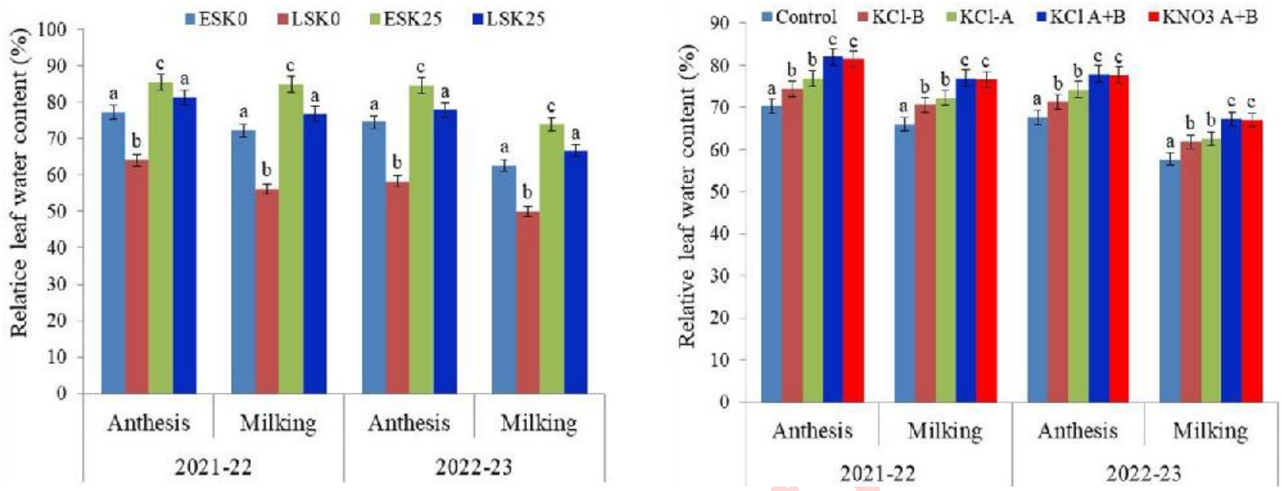

Fig. 2: Integrated effect of sowing date, soil application and spray of potassium on relative leaf water content of wheat during 2021-22 and 2022-23.

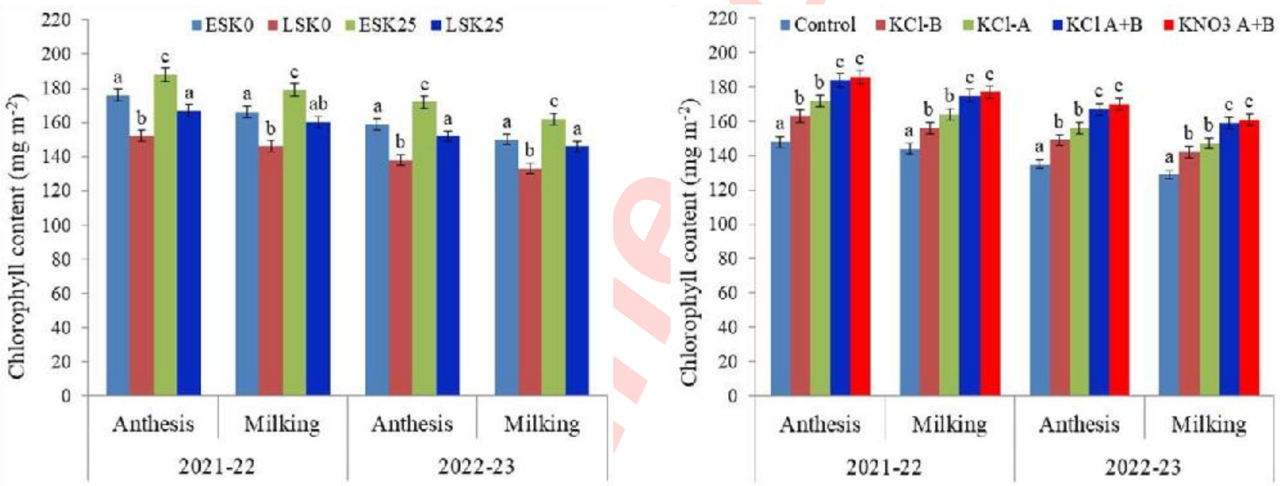

Fig. 3: Integrated effect of sowing date, soil application and spray of potassium on chlorophyll content of leaves of wheat during 2021-22 and 2022-23

During both years, LSK_0 showed significantly higher proline content of straw after anthesis and in grains of wheat (Fig. 4) compared to ESK_{25}, ESK_0 and LSK_{25}. During both years, proline content after anthesis and in grains was at par in ESK_0 and LSK_{25}, but significantly lower than LSK_0. Similarly, the proline content after anthesis and in grains was significantly increased in control (no spray) compared to KClA, KClB, KCl B+A and KNO_3B+A.

One spray of KCl at booting or anthesis were at par for proline content during both years at anthesis and in grains of wheat, but significantly lower than control. However, two sprays of KCl and KNO_3 at booting and anthesis were at par with each other for proline content during both the years at anthesis in leaves and grains. Delay in wheat sowing exposes wheat to high temperature which results in high proline content as a physiological response to heat stress, acting as an osmoprotectant and antioxidant to mitigate damage (Besaliev *et al.,* 2021). Proline helps to maintain cellular homeostasis by scavenging reactive oxygen species and protecting membrane integrity. Potassium application significantly decreases the heat induced accumulation of proline by improving osmotic adjustment and reducing the overall severity of heat induced oxidative stress, which lowers the plant's need to produce excess proline as an emergency osmolyte (Sarwar *et al.,* 2022).

Both years pooled data showed that ESK_{25} significantly increased the net photosynthesis rate (NPR) by 70.6 per cent, stomatal conductance (SC) by 108.8 per cent, transpiration rate (TR) by 25.9 per cent of wheat (Fig. 5) compared to LSK_0 . NPR, SC and TR after anthesis and milking were at par in ESK_0 and LSK_{25}, but significantly higher than LSK_0. The application of K increased the activity of superoxide dismutase and reduced abscisic acid, which

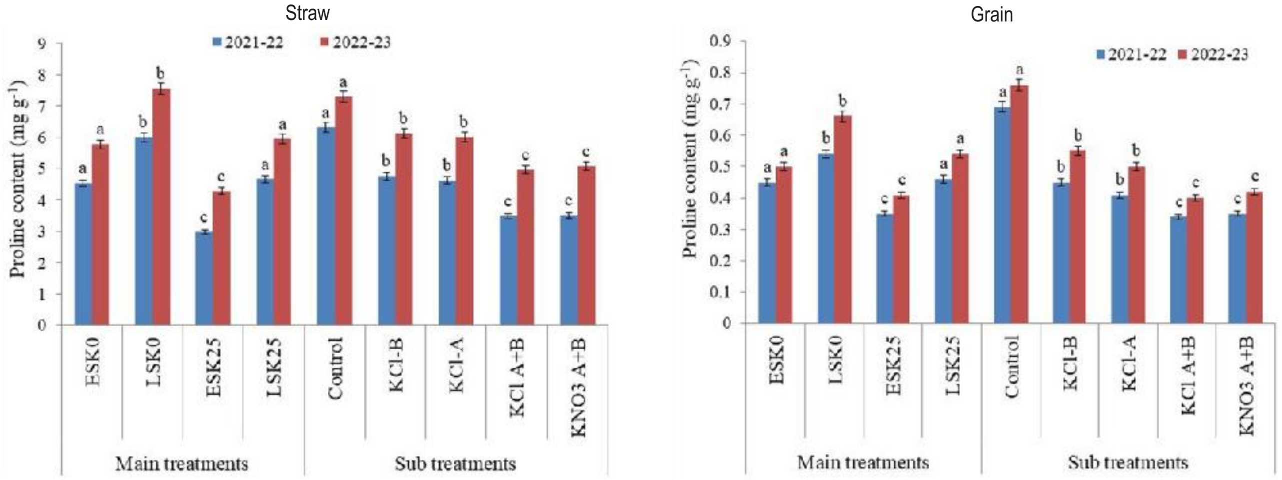

Fig. 4: Integrated effect of date of sowing, soil application and spray of potassium on proline content in straw and grains of wheat during 2021-22 and 2022-23.

regulates stomatal conductance thereby increasing CO_2 intake, synthesis of ATP and enzymes responsible for photosynthesis (Lotfi *et al.,* 2022). During both years, NPR, SC and TR after anthesis and at milking was significantly increased with 2% foliar spray of KCl B+A or KNO_3 B+A than control (no spray), KCl B or KCl A.

One spray of KCl at booting or anthesis were at par for NPR, SC and TR of wheat, but significantly higher than control. However, two sprays of KCl and KNO_3 at booting and anthesis were at par with each other for NPR, SC and TR during both years at both crop growth stages. Rehman *et al.* (2021) also reported that early sowing wheat is escaped from the heat and water stress at anthesis compared to late sowing, which improved the physiological and morphological traits of wheat. Late sown wheat suffers from high temperature stress which reduces SC, TR and NPR. Increase in net photosynthesis rate, stomatal conductance and transpiration rate with soil application and foliar spray of potassium strengthens leaf physiological functions and maintains photosynthetic capacity (Hasanuzzaman *et al.,* 2018; Ali *et al.,* 2019; Tanin *et al.,* 2023). Sarwar *et al.* (2022) also found that 2% foliar K significantly restored net photosynthetic rate by reducing cellular membrane damage in the heat-stressed plants. This physiological recovery and activation of plant defensive system by K under high-temperature stress protected the growth and grain development.

During both years, ESK_{25} significantly increased days taken to heading (H), anthesis (A), milking (M), dough (D) and maturity (MT) of wheat (Fig. 6) compared to ESK_0, LSK_0 and LSK_{25}. During 2021-22, days to heading were increased by 18, 11 and 6 days with ESK_{25}, ESK_0 and LSK_{25}, compared to LSK_0 and these values during 2022-23 were 17, 11 and 7 days. Similarly, during 2021-22, days to maturity increased by 26, 15 and 8 days with ESK_{25}, ESK_0 and LSK_{25} compared to LSK_0 and these values during 2022-23 were 27, 17 and 11 days. Days taken to heading, anthesis, milking, dough and maturity were at par in ESK_0 and LSK_{25}, but significantly more than LSK_0. During both years, days taken to milking, dough and maturity were significantly increased with foliar spray of KCl B+A or KNO_3 B+A than control (no spray), KCl B and KCl A. During 2021-22, days to maturity increased by 21, 20, 10 and 7 days with KClB+A, KNO_3B+A, KCl A and KCl B compared to control and respective values during 2022-23 were 19, 16, 9 and 7 days, respectively.

One spray of KCl at booting or anthesis was at par for days taken to milking, dough and maturity during both years, but significantly more than control. However, KCl B+A and KNO_3B+A were at par with each other for days taken to milking, dough and maturity during both years. Jalota *et al.* (2014) also reported reduction in crop maturity by 23–30 days over different locations in Punjab due to increase in temperature during maturity in late sown wheat. Delay in maturity of wheat with application of potassium in soil has already been reported by Ali *et al.* (2019). The negative effects of late sowing of wheat on maturity can be mitigated by foliar spray of potassium (Singh and Singh, 2020). Munsif *et al.* (2015) also studied the influence of sowing dates on phenological development and concluded that early sowing on mid-October shows prolonged phenological traits and higher yield with long stature plants than later sowing (15^{th} November). Furthermore, high temperature also affects some physiological processes, mainly impairment in photosynthesis and respiration, disintegration of chlorophyll, damage to photosystem II of the photosynthetic apparatus (Pradhan *et al.,* 2012).

Total water input (I+R) were 382.7 mm in both ES and LS of wheat during 2021-22 and corresponding value during 2022-23 was 362.9 mm (Fig. 7). Evapotranspiration (ET) was 315.3, 351.8, 303.4 and 324.9 mm in ESK_0, ESK_{25}, LSK_0 and LSK_{25} during 2021-22 and corresponding values during 2022-23 were 343.8, 380.1, 292.4 and 313.3 mm. Pooled analysis found that

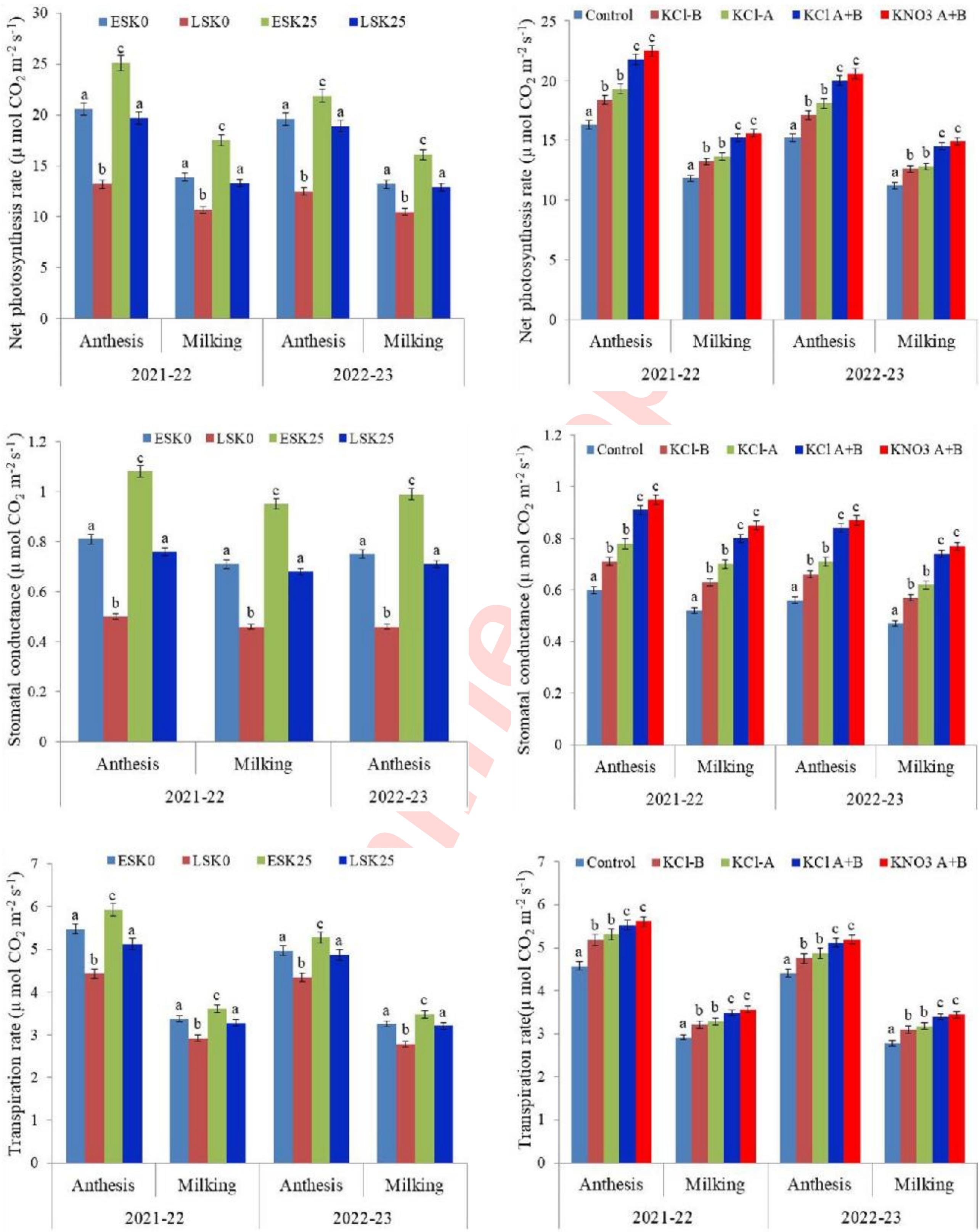

Fig. 5: Integrated effect of date of sowing, soil application and spray of potassium on net photosynthesis rate, stomatal conductance and transpiration rate of wheat leaves during 2021-22 and 2022-23.

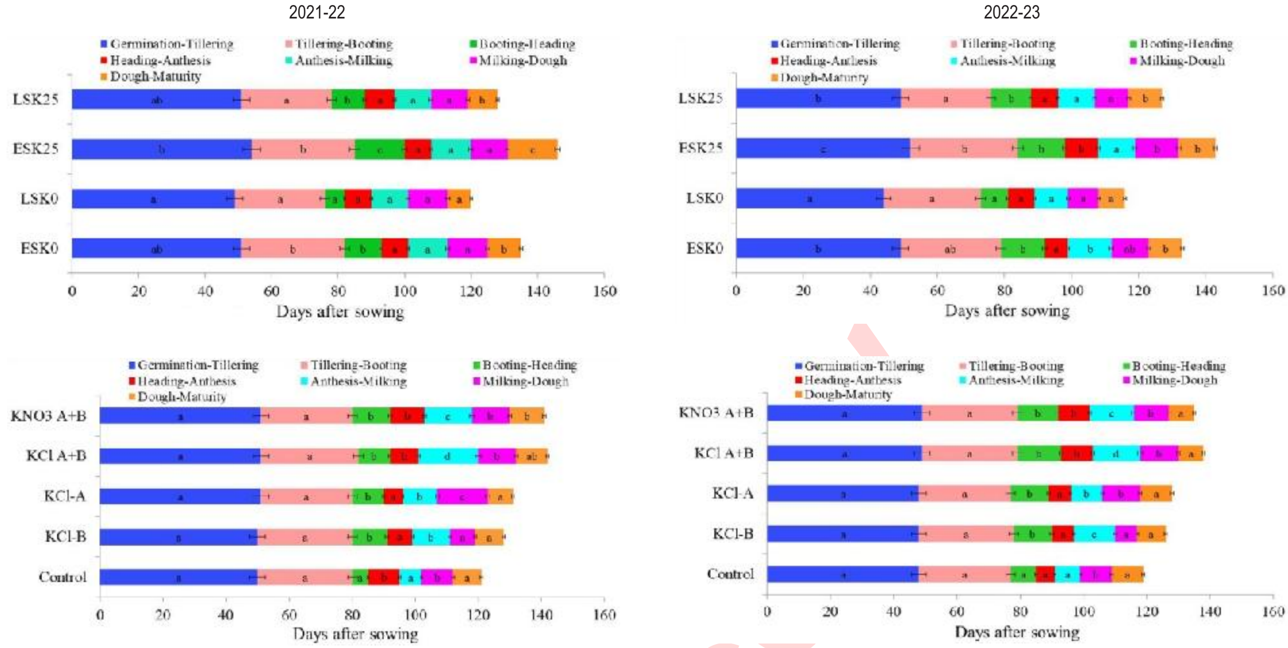

Fig. 6: Integrated effect of date of sowing, soil application and spray of potassium on phonological stages of wheat during 2021-22 and 2022-23.

Fig. 7: Integrated effect of date of sowing, soil application and potassium spray on soil water balance components in wheat during 2021-22 and 2022-23.

ESK_{25} increased ET by 22.9 per cent over LSK_0. During 2021-22, evapotranspiration loss of water with KClB, KClA, KClB+A and KNO_3 B+A increased by 7.7, 12.3, 33.4 and 41.2 mm compared to control in ES wheat and corresponding values in LS were 2.1, 20.5, 47 and 40.5 mm over control. During 2022-23, ET in KClB, KClA, KClB+A and KNO_3 B+A increased by 2, 13.3, 28 and 41.8 mm over control in ES and corresponding values in LS were 1.3, 20.4, 32.1 and 48.9 mm control, respectively. Similarly, Imran *et al.* (2014) observed increase in evapotranspiration of wheat with application of potassium due to increase in the chlorophyll content and days to maturity. Drainage was significantly higher in K_0 in comparison to K_{25} in both sowing dates during 2021-22 due to high rainfall, whereas insignificant drainage was observed during 2022-23. Irrigation application was 225 mm in both ES and LS during 2021-22. However during 2022-23, irrigation application was 225 and 150 mm in ES and LS of wheat. Soil moisture storage was generally less in soil with K_{25} in both years compared to K_0 due to more extraction of water by crop as a result of higher ET. The increase in evapotranspiration because of improvement in crop phenology with early sowing and potassium addition into soil and spray of K leads to higher grain yield of wheat (Fig. 8), as there was a positive and significant correlation

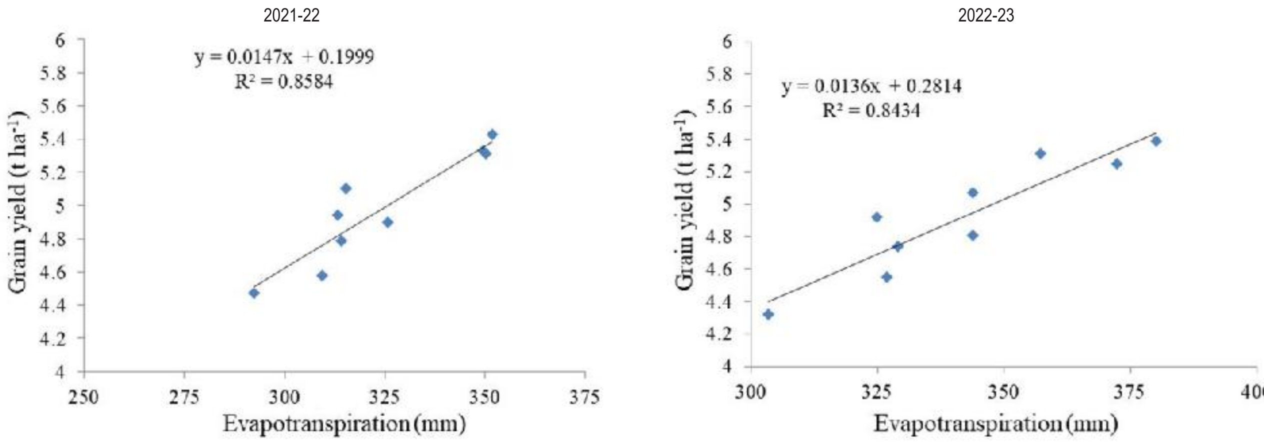

Fig. 8: The relationship of evapotranspiration and grain yield of wheat during 2021-22 and 2022-23.

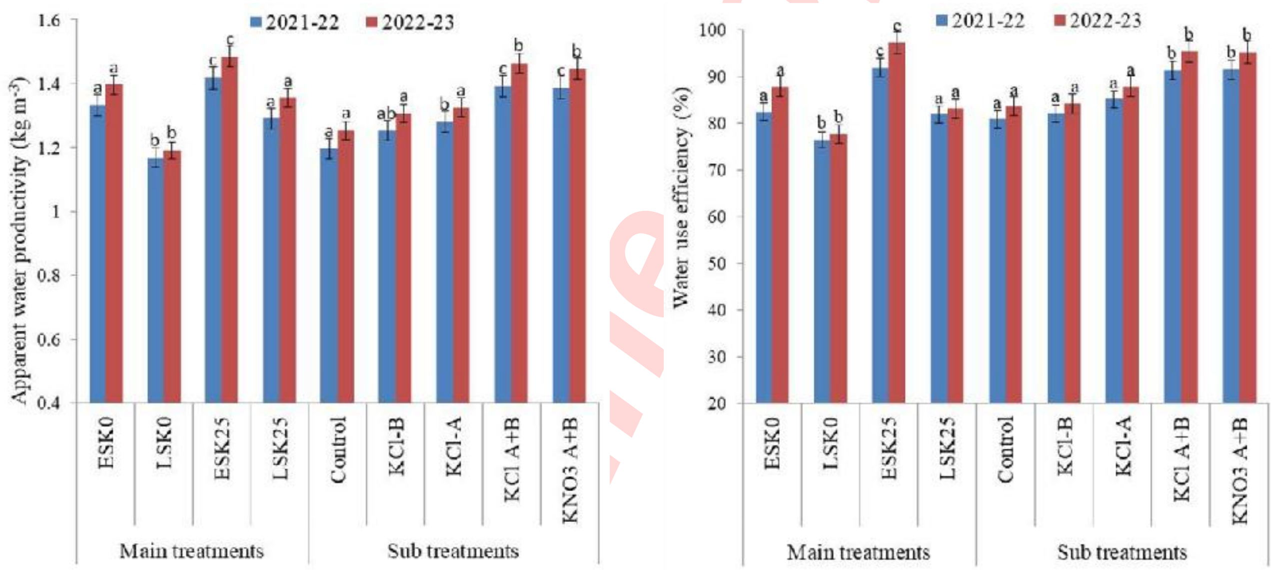

Fig. 9: Integrated effect of date of sowing, soil application and spray of potassium on apparent water productivity and water use efficiency of wheat during 2021-22 and 2022-23.

with water use and grain yield. The apparent water productivity and water use efficiency of wheat was significantly higher in ESK_{25} compared to ESK_0, LSK_0 and LSK_{25} treatments during both years (Fig. 9). During 2021-22, apparent water productivity increased by 21.5, 14.1 and 10.5 per cent in ESK_{25}, ESK_0 and LSK_{25} over LSK_0 and corresponding values during 2022-23 were 24.8, 17.4 and 13.9 per cent. During 2021-22, the water use efficiency increased by 15.5, 6.0 and 5.5 per cent in ESK_{25}, ESK_0 and LSK_{25}, respectively, over LSK_0 and corresponding values during 2022-23 were 19.6, 10.3 and 5.5 per cent. However, apparent water productivity and water use efficiency of wheat was at par in ESK_0 and LSK_{25} during both years, but significantly higher than LSK_0 (Fig. 9). Likewise the apparent water productivity and water use efficiency of wheat in potassium spray through KClA+B and KNO_3A+B were at par, but significantly higher than control, KCl-A and KCl-B, respectively.

Apparent water productivity increased by 16.4 and 16.7 per cent during 2021-22 and 2022-23 with KCl A+B or KNO_3A+B over control. During 2021-22, the water use efficiency increased by 10.5 and 10.7 per cent in KCl A+B and KNO_3A+B over control and the corresponding values during 2022-23 were 11.7 and 11.6 per cent. During 2021-22, the apparent water productivity in KCl-A was significantly higher than control. However, no significant difference in water productivity and water use efficiency was observed among KCl-A, KCl-B and control during both years.

Table 1: Pearson correlation among physiological parameters and grain yield of wheat for pooled data of two years

	Chl-A	Chl-M	RLWC-A	RLWC-M	TR-A	TR-M	NPR-A	NPR-M	SC-A	SC-M	Proline	DTM
Chl-A	1											
Chl -M	1	1										
RLWC- A	0.84	0.84	1									
RLWC- M	0.85	0.86	0.95	1								
TR-A	0.88	0.87	0.88	0.88	1							
TR-M	0.84	0.82	0.86	0.79	0.94	1						
NPR-A	0.17^{ns}	0.13^{ns}	0.39*	0.15^{ns}	0.25^{ns}	0.5	1					
NPR-M	0.68	0.72	0.51	0.7	0.59	0.40*	-0.47	1				
SC-A	0.81	0.82	0.92	0.93	0.85	0.84	0.35*	0.57	1			
SC-M	0.82	0.82	0.93	0.93	0.86	0.84	0.36*	0.57	1	1		
Proline	-0.11^{ns}	-0.06^{ns}	-0.24^{ns}	-0.04^{ns}	-0.25^{ns}	-0.48	-0.85	0.54	-0.22^{ns}	-0.22^{ns}	1	
DTM	0.7	0.72	0.64	0.73	0.5	0.36*	-0.23^{ns}	0.75	0.59	0.59	0.38*	1
GY	0.9	0.89	0.89	0.82	0.81	0.86	0.49	0.42	0.87	0.88	-0.36*	0.58

ns- Non Significant, *correlation is significant at 0.05 level. All other correlations are significant at 0.01 level. Chl-A and M is chlorophyll content at anthesis and at milking, RLWC-A and M is relative leaf water content at anthesis and milking, TR-A and M is transpiration rate at anthesis and milking, NPR-A and M is net photosynthesis rate at anthesis and milking, SC-A and M is stomatal conductance at anthesis and milking, DTM-Days to maturity, GY-Grain yield

Improvement in water productivity and water use efficiency of wheat with soil application of potassium may be due to increase in water uptake through increased area of root contact in soil with potassium (Vijaykumar *et al.,* 2022). The grain yield was significantly (at 0.01 level) and positively correlated with chlorophyll, relative leaf water, transpiration rate, net photosynthesis rate, stomatal conductance and days to maturity of wheat (Table 1), except for proline content, which was negatively and significantly (at 0.05 level) correlated with grain yield, indicating improvement in grain yield with early date of sowing, soil application and potassium spray under heat stress. The improvement in physiological parameters in early sowing shielded the crop from heat stress. Soil application of potassium was more beneficial in late sowing than early sowing. Application of potash through spray was also beneficial in both early and late sowing indicating more requirement of potassium during heat stress. Improvement in chlorophyll content with potash application was also significantly and positively correlated with RLWC, TR, SC and days to maturity, which further enhanced crop growth and grain yield.

In conclusion, this study highlights the practical importance of integrating timely sowing with optimized potassium nutrition to sustain wheat productivity under rising temperature conditions. Potassium application, particularly when supplemented with foliar sprays at critical growth stages, enhanced physiological resilience, improved water-use efficiency and reduced heat-induced stress, resulting in higher grain yield. These findings provide a relevant and cost-effective management strategy for farmers in heat-prone wheat-growing regions and contribute to the development of climate-resilient wheat production systems.

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