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BIOCHEMICAL, PHYSIOLOGICAL AND YIELD RESPONSE OF CANOLA (*BRASSICA NAPUS* L.) WITH EXOGENOUS APPLICATION OF POTASSIUM AND REDUCED SEED RATE UNDER IRRIGATION REGIMES

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Abstract

Crop productivity is affected by agronomic practices such as Seed rate, fertilizer and irrigation application. A field trial with different agronomic practices was laid out to improve canola productivity and alleviate drought stress with potassium. The experiment included three factors, Factor A: irrigation regimes *i.e.* I_0 = Conventional (control), I_1 = Vegetative + bud formation + flowering, I_2 = Vegetative + bud formation + grain development, I_3 = Vegetative + flowering + grain development, I_4 = Bud formation + flowering + grain development), Factor B: exogenous application of potassium (K_1= recommended and K_2= split application of 1/3 soil + 1/3 fertigation + 1/3 foliar), and Factor C: seed rates (S_1= recommended (2 kg per acre) and S_2= reduced (1.5 kg per acre). Results showed that a dramatic response of irrigation regimes was noticed under the potassium application and seed rate. Maximum antioxidant activity of SOD, POD, and CAT was measured in the I_0 treatment (conventional irrigation) with the exogenous application of potassium (K_2) and reduced seed rate (S_2). Exogenous application of potassium significantly improved the grain yield (2.5%) and biological yield (1.85%) when compared with the recommended treatment (K_1). The same trend was also noticed for reduced seed rate. Grain yield and biological yield (3.38% and 2.61%) increased significantly with reduced seed rate when compared with the recommended seed rate, respectively. It is concluded that by improving agronomic practices like with the exogenous application of potassium with reduced seed rate under I_3 treatment (vegetative + flowering + grain development stage).

Key words: Canola; Antioxidant activity; Exogenous application; Irrigation regimes; Seed rate

Introduction

Canola is an oilseed crop, and it can be cultivated in Pakistan over an area of 0.03 million hectares while the yield per unit area is far less in comparison to other countries (Anon., 2022). The main reason for the lower canola yield is the lack of improved production technology in agriculture and most of the farmers are using traditional ways for crop production. Improved agronomic practices can increase farm income by reducing input cost.

One of the major factors limiting global food crop production is the drought, which results in significant drops in crop productivity. While drought frequently results in flower abortion, affects water balance, and causes imbalances in the source-sink relationship, as well as various physiological and biochemical processes in plants, enough water is required for optimal growth, development, transpiration, and photosynthetic activities (Farouk & Amany, 2012; Malekpoor *et al*., 2016). Drought-related changes in metabolic processes lead to the formation of reactive oxygen species, which in turn cause oxidative damage (ROS). Lipids, nucleic acids, soluble proteins, and chlorophyll pigments are undoubtedly damaged by the production of reactive oxygen species (ROS), which include hydrogen peroxide (H_2O_2), superoxide anions (O_2), and hydroxyl radicals (OH); nevertheless, these also causes membrane leakage, inhibition of the photosynthetic electron transport chain, and CO_2 fixation (Shabbir *et al*., 2016; Lang *et al*., 2018; Wada *et al*., 2019). The exogenous supply of mineral nutrients to plants is currently popular for reducing losses caused by drought stress. Potassium (K) application is essential in the development of plant resistance mechanisms through osmotic adjustment linked to membrane potential, enzyme activation, water absorption, and cell turgor maintenance (Adams and Shin, 2014; Shafiq *et al*., 2015).

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According to Saleem *et al*., (2020), crop nutrition is thought to be a significant factor in the rise and fall in the yield of many crops. Nutritionists have confirmed that canola oil's high antioxidant and fatty acid content, along with its excellent quality, are the reasons behind its rapidly rising demand (Abbadi & Leckband, 2011). However, because of insufficient resource utilization and nutrient management techniques, the production potential of canola in developing nations like Pakistan is still unrealized (Ghosh *et al*., 2000). The main cause of canola's decreased yield per unit area is a poor nutrient supply (Ahmad *et al*., 2007). Under dry and semi-dry conditions, nutrient management techniques may be very helpful in boosting its production (Suzer, 2015). Potassium is a macronutrient essential for optimal functioning of plants. The majority of soil potassium (K) is predominantly found either within the exchangeable fraction or encapsulated within silicate minerals. Consequently, the ongoing extraction of K from the exchangeable fraction via the harvest of grains and other agricultural products may lead to the gradual depletion of K in the soil, as elucidated by Pal *et al*., (2021). Potassium (K) serves as a vital macronutrient crucial for optimizing crop growth, and it plays a significant role in bolstering plant tolerance to water scarcity, as highlighted by Ahmad *et al*., (2018). Previous research findings have consistently demonstrated the favorable effects of K application on the physiological aspects, yield, and components related to yield in oilseed crops under conditions of water stress, as exemplified by (Fanaei *et al*., 2012). Potassium (K) plays a pivotal role in maintaining lower water potential in crops when faced with restricted water availability. Its multifaceted functions encompass the activation of enzymatic processes within plants, facilitation of various physiological functions, modulation of stomatal aperture, and enhancement of water-related attributes in plants when water resources are limited (Reddy *et al*., 2004; Waraich *et al*., 2011). Therefore, an experiment was conducted to evaluate the optimized seed rate, irrigation management, and application method of K dose for productivity enhancement of canola in Pakistan.

Material and Methods

Site and design: The experiment was laid out at the Agronomic Research Area, Institute of Agronomy, Bahauddin Zakariya University, Multan, Pakistan. The experiment was designed in randomized complete block design (RCBD) with split-split arrangement and was repeated thrice.

Experimental treatments: The experiment included the three factors, Factor A: irrigation regimes *i.e.* I_0 = Conventional (control), I_1 = Vegetative + bud formation + flowering, I_2 = Vegetative + bud formation + grain development, I_3 = Vegetative + flowering + grain development, I_4 = Bud formation + flowering + grain development), Factor B: application of potassium (K_1= recommended and K_2= split application of 1/3 soil + 1/3 fertigation + 1/3 foliar), and Factor C: seed rates (S_1= recommended and S_2= reduced). Irrigation was designed in the main plot, potassium application was placed in the sub-plot, and seed rate was adjusted in the sub-sub plot. A 2 kg per acre seed rate was used in recommended and 1.5 kg per acre seed was used in reduced treatment. Soil application was the recommended application of potassium. In K_2 treatment, application of potassium was applied in three splits. 1/3 of the recommended potassium was applied at the time of sowing, 1/3 was applied at the 1st irrigation by fertigation and the remaining 1/3 was applied by foliar application at three different stages.

Crop husbandry: Soil was cultivated three times with the help of a cultivator and was rotavating for seedbed preparation. An approved variety of canola seed “Canzola” was collected from an authorized dealer of Punjab Seed Corporation. The seed was treated with a fungicide @2g per kg “Thiophanate methyl” to eliminate any seed-borne disease before sowing. A fine seedbed was prepared, and the seed was drilled in the soil as par treatment with enough moisture for germination with the manual drill at a depth of 2 cm. A recommended dose of nitrogen (35 kg per acre) and 35 kg per acre phosphorus was applied while potassium was applied @25 kg per acre (GOP, 2021). A recommended dose of nitrogen was applied in three splits, half of the dose was applied at the time of sowing, half of the remaining was applied at the time of 1st irrigation and the remaining was applied at the flowering stage. A whole dose of phosphorus was applied at the time of sowing. Potassium was applied in three splits. 1/3 was applied at the time of sowing and was broadcast at the time of seedbed preparation. 1/3 was applied at the first irrigation by the fertigation method. The remaining dose of potassium was applied in foliar form in three equal splits at the three different stages bud formation, flowering, and pod formation stage. Urea (46% nitrogen), diammonium Phosphate (18% nitrogen and 46% phosphorus) and murate of potash (60% K_2O) Irrigation was applied as par experimental treatment. To avoid weed infestation during the experiment, pre-emergence herbicide *s-metolachlor* was sprayed, while *Lambda cyhalothrin* was used for insect control. The crop was harvested at its physiological maturity.

Data collection

Biochemical analysis: To assay biochemical analysis, fresh leaves from each experimental unit were collected at the pod formation stage. Polyphenol oxidase (PPO), catalase (CAT), and peroxidase (POD) activity were assayed by Kumar and Khan (1982), Singh and Sharma (2010), and Gueta-Dahan *et al*., (1997), respectively. The reaction mixture contains 1 ml catechol, 0.1 M phosphate buffer (7.8 pH), and 5 ml enzyme extract was incubated for 5 min at 25°C. The reaction was terminated by dissolving 1 ml of 3 ml NH2SO4. The PPO was determined at 495 nm and was expressed as Umg^{-1} (U = change in 0.1 absorbance min^{-1}, mg^{-1} protein. Catalase (CAT) activity was determined at 240 nm for 2 minutes with an interval of 20 seconds and expressed as Ug^{-1}. The peroxidase (POD) activity was determined at 470 nm for two minutes with an interval of 30 seconds. This reaction solution consisted of 1 ml of guaiacol, 0.3 ml of enzyme extract, 2.5 ml of 50 mM potassium buffer (7.0 pH), and 1 ml of 1% H_20_2 for 2 min in the reaction mix. Superoxide dismutase (SOD) activity was determined by Gueta-Dahan *et al*., (1997), the estimation of the volume of enzyme affected as 50% inhibition of nitro blue tetrazolium. Malondialdehyde contents (MDA) were determined by Janero (1990). For this 0.5 g of fresh leaves was homogenized in 5% trichloroacetic acid (5 ml), heated for 10 minutes at 25ºC and was centrifuge at 1800g. The 2-thiobarbituric acid (TBA) was added to the supernatant, placed at 98ºC for 10 minutes, and then cooled at room temperature. The absorbance was recorded with a spectrophotometer at 532 nm.

Physiological attributes: By using the acetone extraction procedure, chlorophyll a and b were measured (Arnon, 1949). Fresh leaf samples were collected from the field and shifted to the lab in an ice bucket. A 0.2 g sample of leaves was obtained, minced into tiny pieces, and put in 80% acetone at 4°C for an entire day before being centrifuged for 10 min. at 8000 rpm. At 645 nm and 663 nm, spectrophotometer readings were taken. Values were computed using a formula presented by Nagata & Yamashita (1992). Total chlorophyll content was measured by (chlorophyll a + chlorophyll b).

Quality attributes: For oil extraction, seeds were dried and grounded coarsely and packed carefully for oil extraction. This extraction was performed continuously for three cycles (90-120 min.) Oil contents were determined by using micro-Kjeldahl method (Bremner, 1965) and its protein content was evaluated by multiplying the N content by a conversion constant of 5.75 (Mosse, 1990).

Mineral uptake (NPK): For phosphorus and potassium contents determination, seed samples were collected from each treatment and were dried at 70ºC for 48 hours. Seed samples were grinded into powdered and 0.5 g samples were digested with 20 ml concentrated nitric acid by adopting method of Rathje and Jackson (1958). The samples were placed at room temperature for three hours and after that were laid on the digestion block at 250ºC until solution became tinted yellow in appearance. The solution was diluted with 50 ml of distilled water and was filtered with filter paper. The phosphorus contents were determined with spectrophotometer by recording optical density at 430 nm by Primson *et al*., (2011). The potassium contents were resolute by a photometer by Tammam (2008). Nitrogen contents were determined by the Kjeldahl apparatus according to the method suggested by Rezaei *et al*., (2018).

Morphological attributes: The crop was harvested manually when the leaves' color started yellowing and 75% pods were turned brown. Ten random plants were selected for growth, yield, and quality parameters. Plant height and pod length were noted with measuring tape. Electronic balance was used to observe the grain yield and biological yield.

Statistical analysis

Data recorded was analyzed statistically using the least significant difference (LSD) test at 5% probability (Steel *et al*., 1996). Graphs were prepared in Microsoft tools (MS Word).

Results

Biochemical analysis: Analysis of variance for biochemical analysis (PPO, CAT, POD, SOD, MDA, TSS and Proline) showed a significant (p<0.01) interaction of irrigation regimes to the application of potassium and seed rate (Fig. 1). Among the irrigation regimes, the maximum antioxidant activity and lipid peroxidation activity was observed in the control treatment while the minimum activity of the biochemical analysis was observed in the I3 treatment. A dramatic response of irrigation regimes was noticed in biochemical analysis. Between the applications of potassium, the exogenous application of potassium showed the maximum activity vs. the traditional application regarding biochemical analysis. Exogenous application of potassium increases the biochemical activity of the plant. As it is concerned with the seed rate, reduced seed rate as compared to the recommended seed showed the maximum biochemical activity.

Concerning the PPO and POD activity, the maximum values (2.09 vs. 0.46) and (2.84 vs. 0.15) were observed in I0 (conventional irrigation) with reduced seed rate and exogenous application of potassium, respectively. Exogenous application of potassium increased the PPO and POD activity (12.4 and 9.6%) in traditional application as compared to exogenous application. The highest CAT and SOD values (2.59 vs. 0.20) and (1.72 vs. 0.26) were measured I0 with reduced seed rate and conventional application of potassium, respectively. A decrease in the value (2 and 0.6%) was noticed with the exogenous application of potassium as compared to recommended application, respectively. MDA, TSS and proline showed the maximum value (7.16 vs. 2.22), (42.7 vs. 29.1) and (31.69 vs. 15.10) were observed in the I0 (conventional irrigation) with reduced seed rate and exogenous application of potassium, respectively. Exogenous application increased the MDA, TSS and proline (14.1%, 10.5% and 17.4%), respectively.

Physiological and quality attributes: A significant (p<0.01) effect of irrigation regimes to the application of potassium and seed rate was also notices regarding the quality and physiological attributes of canola (Fig. 2).

Results for quality attributes showed that the exogenous application of potassium significantly increased the quality of canola crops under all treatments. Concerning the seed oil and protein contents, the maximum seed oil and protein contents (40.5 and 41.7%) was measured in the I3 treatment with the exogenous application of potassium with reduced seed rate as compared to the minimum seed oil and protein contents (35.1 and 33.7%) in recommended seed rate with the tradition application under I2 and I0 treatment, respectively. The canola performed better with a reduced seed rate. Concerning the physiological attributes, the maximum values for chlorophyll a, chlorophyll b and total chlorophyll contents. The maximum values for chlorophyll a (11.47), chlorophyll b (8.20) and total chlorophyll contents (19.7) were measured in the I3 treatment with the exogenous application of potassium under reduced seed rate. The same trend for the increase in physiological attributes was noticed in quality attributes. The minimum values for chlorophyll a, chlorophyll b, and total chlorophyll contents (8.30, 4.27 and 12.6) were measured in the I0 treatment with the traditional application of potassium under the recommended seed rate.

Mineral uptake: Mineral uptakes like nitrogen, phosphorus and potassium uptake were also significantly affected by the irrigation regimes, application of potassium and seed rate (Fig. 3).

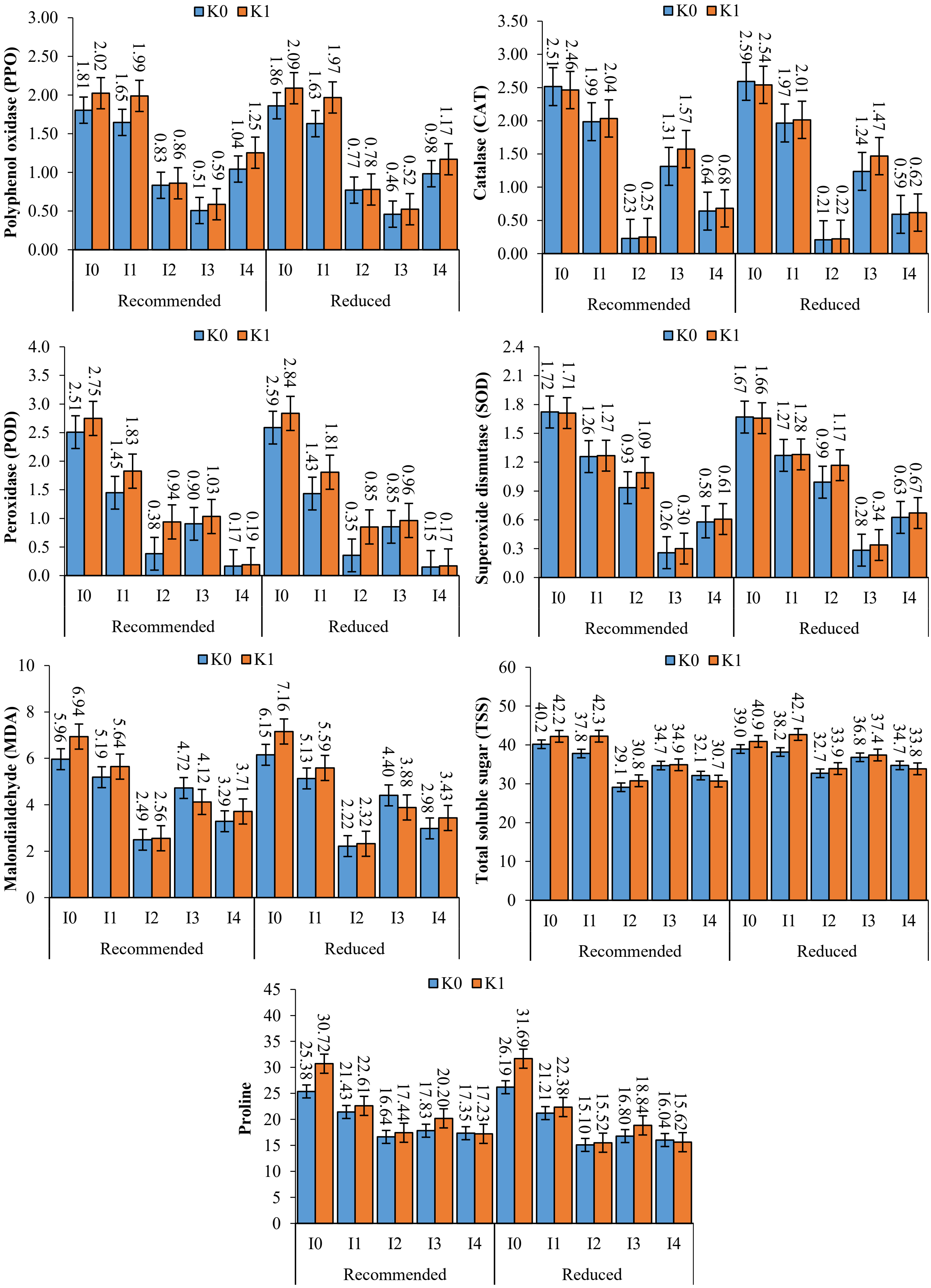

Fig. 1. Biochemical attributes of canola affected by the indigenous application of potassium (K) with reduced seed rate and irrigation regimes. I_0 = Control (at vegetative + bud formation + flowering + grain development stage), I_1 = vegetative + bud formation + flowering stage, I_2 = vegetative + bud formation + grain development stage, I_3 = vegetative + flowering + grain development stage, I_4 = bud formation + flowering + grain development, K_0 = Recommended, K_1 = 1/3 soil + 1/3 fertigation + 1/3 foliar application.

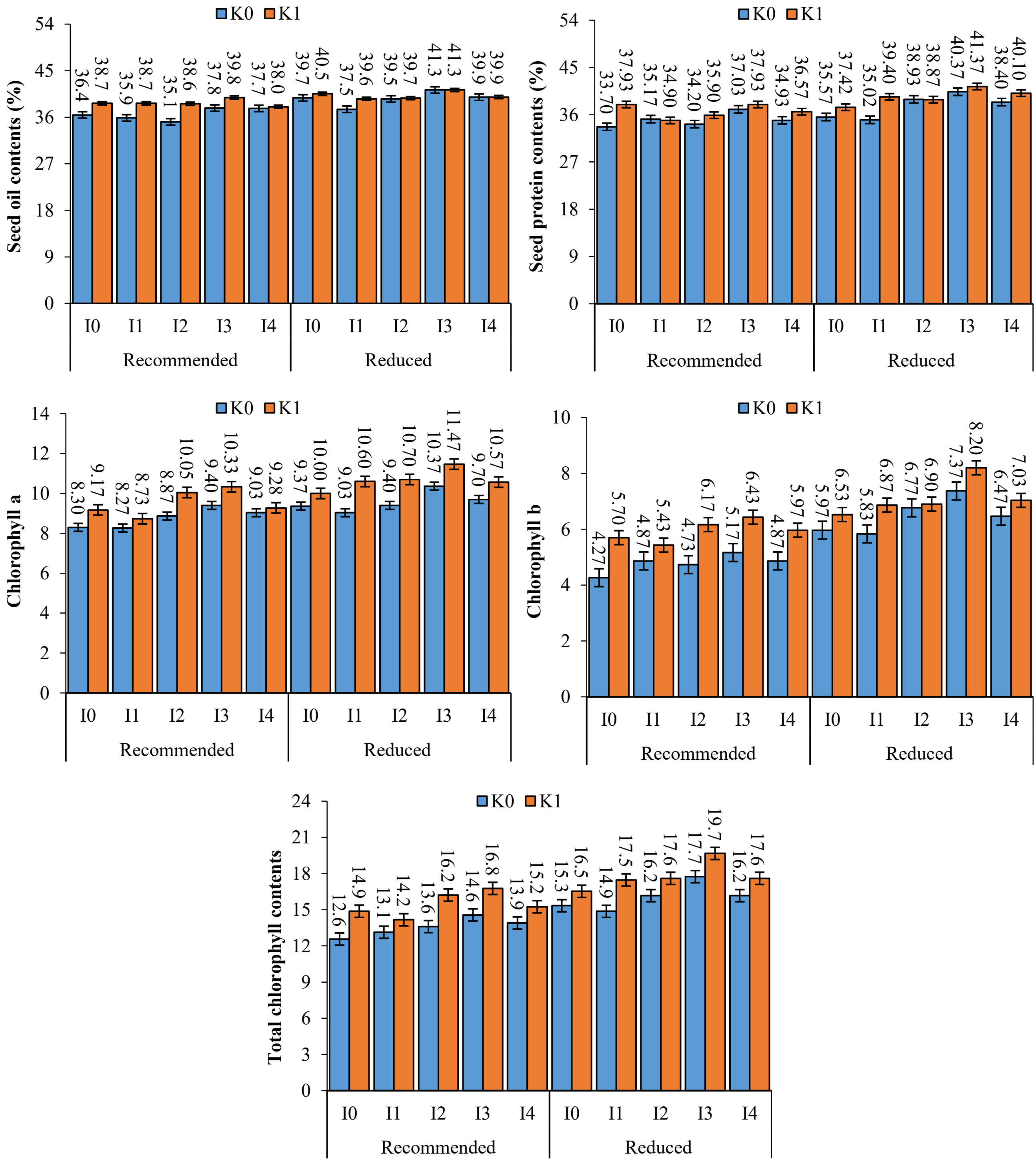

Fig. 2. Crop physiology and quality attributes of canola affected by the indigenous application of potassium (K) with reduced seed rate and irrigation regimes. I_0 = Control (at vegetative + bud formation + flowering + grain development stage), I_1 = vegetative + bud formation + flowering stage, I_2 = vegetative + bud formation + grain development stage, I_3 = vegetative + flowering + grain development stage, I_4 = bud formation + flowering + grain development, K_0 = Recommended, K_1 = 1/3 soil + 1/3 fertigation + 1/3 foliar application.

Exogenous application of potassium improved the mineral uptake and thus maximum nitrogen (8.97%), phosphorus (2.97%) and potassium contents (2.70%) were observed with the exogenous application of potassium in I3 treatment with reduced seed rate as compared to the other treatments. A dramatic role of irrigation and potassium application was noticed in nutrient uptake. The minimum nitrogen (4.37%), phosphorus (1.13%) and potassium (1.04%) were noted in traditional potassium application with the recommended seed rate under I_0, I4 and I2 treatment, respectively.

Growth and yield attributes: Anova results for growth and yield attributes showed that individual effect of irrigation regimes, potassium application and seed rate was significant (p<0.01). Their interactive effect was also significant on growth and yield attributes of canola except phonological attributes, number of branches per plant and number of pods per plant (Table 1).

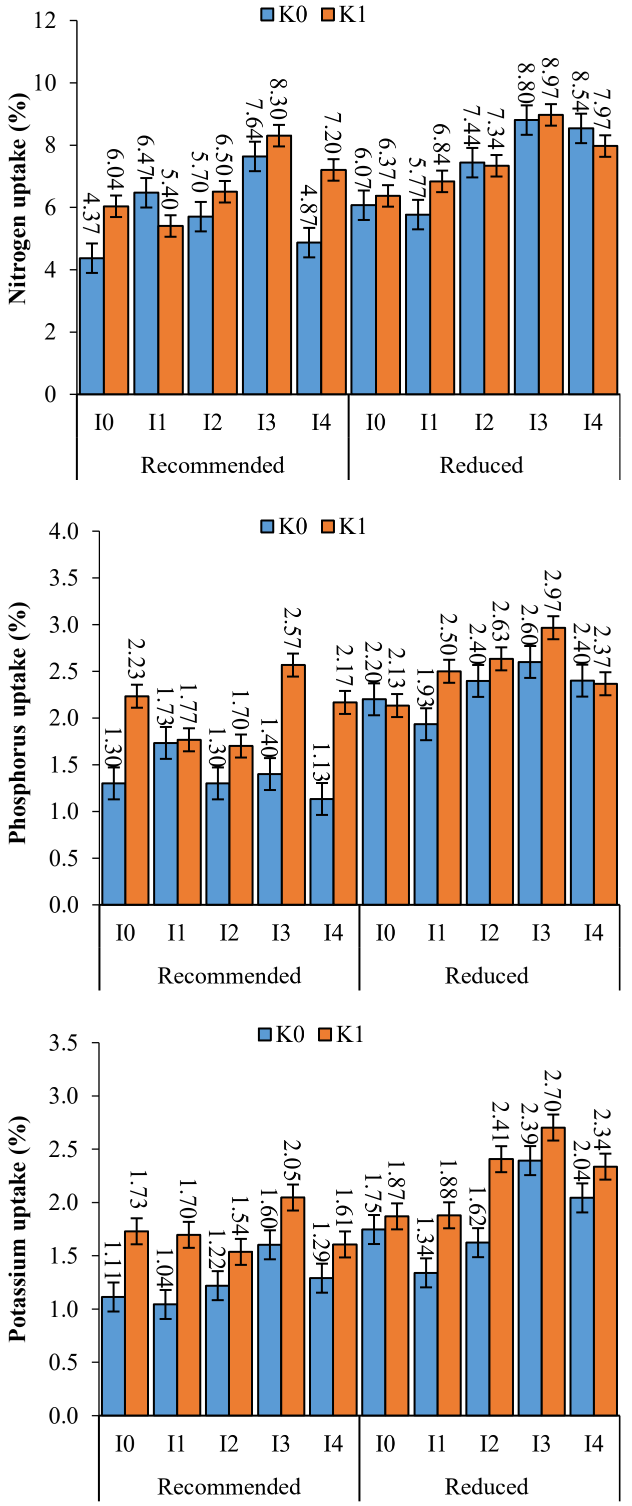

Fig. 3. Nutrient uptakes affected by the indigenous application of potassium (K) with reduced seed rate and irrigation regimes.
I_0 = Control (at vegetative + bud formation + flowering + grain development stage), I_1 = vegetative + bud formation + flowering stage, I_2 = vegetative + bud formation + grain development stage, I_3 = vegetative + flowering + grain development stage, I_4 = bud formation + flowering + grain development, K_0 = Recommended, K_1 = 1/3 soil + 1/3 fertigation + 1/3 foliar application.

Concerning the individual effect of irrigation regimes on crop phenology, the maximum days to pod formation (115.7) and days to maturity (129.1) were counted in the I4 treatment followed by the control irrigation and the minimum days to pod formation (108.7) and days to maturity (122.0) were counted in I3 treatment. Concerning the growth attributes, the maximum plant height (154.7 cm), number of leaves (14.7) and number of branches per plant (12.6) were counted in the I3 treatment while the minimum values for growth attributes were counted in 138.5 cm, 11.8 and 9.4 in the conventional application. Results for yield attributes showed that maximum number of pods (67.0), seeds per pod (33.5) and pod length (5.63 cm) was measured in I4 treatment and minimum results were measured in conventional irrigation. Furthermore, the same results for 1000-grain weight (6.57 g), grain yield (1990 kg ha^{-1}) and biological yield (2544.2 kg ha^{-1}) were noted.

Between the effects of potassium application, the maximum days to pods formation and days to maturity (115.7 and 129.0) was counted in the recommended application when it was compared with exogenous application, respectively. While the maximum results for plant height (148.6 cm), number of leaves (13.6), number of branches per plant (11.0), number of pods per plants (32.6) and pod length (5.47 cm) was measured in the exogenous application as compare to the recommended application. The same results for yield attributes like, maximum 1000-grain weight (6.21 g), grain yield (1981.9 kg ha^{-1}) and biological yield (2507.0 kg ha^{-1}) were attained in the exogenous application.

Concerning the effect of seed rate, the maximum value for the effect of seed on phenology and growth attributes was noticed with the reduced seed rate when it was compared with the recommended seed rate. The maximum value for the 1000-grain weight (6.33 g), grain yield (1989.7 kg ha^{-1}) and biological yield (2516.3 kg ha^{-1}) were noticed in the reduced seed rate as compared to the recommended seed rate.

Discussion

Our results showed that exogenous application of potassium significantly improved the crop yield (Table 1) by improving biochemical activity (Fig. 1) and crop physiology (Fig. 2) with mineral uptake (Fig. 3). Increased CAT, POX, APX, and SOD activity in response to irrigation regimes indicate increased ROS production. The favorable responses to the application of K for improved plant tolerance to oxidative stress are attributed to their antioxidant scavenging potential against ROS-induced cellular damage (Zhang *et al*., 2018). Similar results have been reported for sugar beetroot (Salami and Saadat, 2013) and wheat (Nawaz *et al*., 2015) and sunflower (Hussain *et al*., 2016), indicating that decreased nutritional availability and antioxidant enzyme activity make plants more vulnerable to oxidative stress. Exogenous application of potassium stimulates the activity of CAT, APX, and SOD, protecting plants from oxidative damage and lipid peroxidation during drought stress (Majeed *et al*., 2018). To avoid extreme dehydration, proline and TSP accumulation in the cytoplasm is induced (Bahrami-Rad and Hajiboland, 2017). Potassium application method and time also played a significant role in enhancing canola productivity. Potassium (K) is an essential nutrient for canola and plays a crucial role in various physiological processes that can impact yield.

Firstly, timely irrigation can mitigate moisture stress during critical growth phases, particularly during flowering and pod development, ensuring optimal conditions for fertilization and seed setting (Mohtashami *et al*., 2020; Katuwal *et al*., 2020). Secondly, consistent moisture availability supports sustained nutrient uptake and transport, fostering nutrient-rich seed development (Karthika *et al*., 2018). Irrigation application at critical growth stages has already been suggested by Saleem *et al*., (2022) in wheat. Moreover, irrigation aids in temperature moderation, preventing extreme heat stress or drought-induced yield losses (Birthal *et al*., 2021). It facilitates weed and pest management by providing the moisture required for the application of herbicides and insecticides, safeguarding canola plants from yield-depleting threats (Coolong, 2013).

Potassium application method and time also played a significant role in enhancing canola productivity. Potassium (K) is an essential nutrient for canola and plays a crucial role in various physiological processes that can impact yield. The application of potassium can trigger increased canola yield through nutrient uptake and transport (Johnson *et al*., 2022), osmotic regulations (Mostofa *et al*., 2022), enzyme activation (Suelter, 1985), improving stress tolerance (Aslam *et al*., 2021) and enhancing flowering and disease resistance (Sardans & Penuelas, 2021).

Reducing the seed rate linearly reduced the yield but it increased when the crop was planted in beds. This might be due to the easy and readily availability of nutrients and water to the crops because plant competition was reduced by bed sowing. Decreasing the seed rate lowered the plant population which resulted in more pods per plant containing the extra number of seeds (Angadi *et al*., 20223). A decrease in branches per plant in canola has been studied by Garcia-Hernandez *et al*., (2022) indicating lower but economical plant population was more beneficial. Higher planting density increased the mortality rate in canola plants whereas, a reduced seeding rate allowed individual plants to explore more resources (Tetteh *et al*., 2019). Potassium application methods were also important in increasing crop yield. Soil-applied K performed better than fertigation and foliar spray because early availability of K helped plant roots to accumulate more K in plant parts which also increased other nutrient uptake and translocation.

Conclusion

It was concluded that the application of potassium, seed rate and irrigation regimes significantly improved the yield and quality of canola by improving biochemical activity, and physiology with nutrient uptake. Among the irrigation regimes, the maximum biochemical activity was observed in conventional irrigation. Maximum yield of canola can be obtained with the exogenous application of potassium, reduced seed rate (1.5 kg per acre) and I^3 treatment (vegetative + flowering + grain development stage).

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Table 1. Least significant difference (LSD) means for comparison of irrigation regimes, exogenous application of potassium and seed rate.

Factors	Phenology		Growth and yield									
Irrigation (I)	**PF**	**DM**	**PH**	**NL**	**BP**	**NP**	**SP**	**PL**	**GW**	**GY**	**BY**	**HI**
I_0	115.2 A	128.5 A	138.7 B	11.8 B	9.4 C	57.1 C	28.1 C	4.96 C	5.47 C	1932.7 E	2434.9 E	2434.9 E
I_1	112.4 B	125.7 B	140.2 B	12.7 B	10.0 C	57.7 C	27.9 C	5.07 BC	5.50 C	1946.5 D	2469.7 D	2469.7 D
I_2	111.7 B	125.1 B	140.5 B	12.2 B	11.1 B	60.4 B	29.4 B	5.04 C	5.68 C	1968.1 B	2478.3 C	2478.3 C
I_3	108.7 C	122.0 C	154.7 A	14.7 A	12.6 A	67.0 A	33.5 A	5.63 A	6.57 A	1990.7 A	2544.2 A	2544.2 A
I_4	115.7 A	129.1 A	138.5 B	13.7 AB	10.7 B	62.2 B	32.7 A	5.20 B	6.04 B	1957.2 C	2494.3 B	2494.3 B
Potassium (K)												
K_1	115.7 A	129.0 A	136.4 A	12.5 B	10.5 B	57.4 B	28.0 B	4.88 B	5.49 B	1932.6 B	2461.5 B	2461.5 B
K_2	109.8 B	123.1 B	148.6 A	13.6 A	11.0 A	64.4 A	32.6 A	5.47 A	6.21 A	1981.9 A	2507.0 A	2507.0 A
Seed rate (S)												
S_1	117.6 A	131.0 A	133.5 B	11.5 B	10.2 B	53.7 B	25.0 B	4.83 B	5.37 B	1924.7 B	2452.2 B	2452.2 B
S_2	107.9 B	121.2 B	151.5 A	14.6 A	11.3 A	68.1 A	35.6 A	5.53 A	6.33 A	1989.7 A	2516.3 A	2516.3 A
SOV	**Analysis of variance**											
Irrigation (I)	**	**	**	ns	**	**	**	**	**	**	**	**
Potassium (K)	**	**	**	*	*	**	**	**	**	**	**	**
I×K	*	*	**	ns	ns	*	ns	ns	ns	**	**	**
Seed (S)	**	**	**	**	**	**	**	**	**	**	**	**
I×S	**	**	**	ns	**	*	**	**	*	**	**	**
K×S	Ns	ns	**	ns	*	*	Ns	*	*	**	**	**
I×K×S	Ns	ns	**	**	ns	Ns	*	**	**	**	*	*

I_0 = Control (at vegetative + bud formation + flowering + grain development stage), I_1 = vegetative + bud formation + flowering stage, I_2 = vegetative + bud formation + grain development stage, I_3 = vegetative + flowering + grain development stage, I_4 = bud formation + flowering + grain development, K_0 = Recommended, K_1 = 1/3 soil + 1/3 fertigation + 1/3 foliar application, PF =Days to pods formation, DM =Days to maturity, PH =Plant height (cm), NL=Number of leaves per plant, BP= Number of branches per plant, NP= Number of pods per plant, SP= number of seeds per pod, PL= pod length (cm), GW= 1000-grain weight (g), GY= Grain yield (kg ha^{-1}), BY= Biological yield (Kg ha^{-1}), HI= Harvest index (%), SOV= Source of variance, *= significant, **= highly significant and ns= non-significant

References

Abbadi, A. and G. Leckband. 2011. Rapeseed breeding for oil content, quality, and sustainability. *Eur. J. Lipid Sci. Technol.*, 113(10): 1198-1206.

Adams, E. and R. Shin. 2014. Transport, signaling, and homeostasis of potassium and sodium in plants. *J. Integ. Plant Biol.,* 56(3): 231-249.

Ahmad, G., A. Jan, M. Arif, M.T. Jan and R.A. Khattak. 2007. Influence of nitrogen and sulfur fertilization on quality of canola (*Brassica napus* L.) under rainfed conditions. *J. Zhejiang Uni. Sci.*, 8: 731-737.

Ahmad, Z., S. Anjum, E.A. Waraich, M.A. Ayub, T. Ahmad, R.M.S. Tariq, R. Ahmad and M.A. Iqbal. 2018. Growth, physiology, and biochemical activities of plant responses with foliar potassium application under drought stress–a review. *J. Plant Nutr.*, 41(13): 1734-1743.

Angadi, S.V., H.W. Cutforth, B.G. McConkey and Y. Gan. 2003. Yield adjustment by canola grown at different plant populations under semiarid conditions. *Crop Sci.*, 43(4): 1358-1366.

Anonymous. 2022. Economic survey of Pakistan. Islamabad: Ministry of Fianance.

Aslam, M.M., F. Farhat, M.A. Siddiqui, S. Yasmeen, M.T. Khan, M.A. Sial and I.A. Khan. 2021. Exploration of physiological and biochemical processes of canola with exogenously applied fertilizers and plant growth regulators under drought stress. *Plos One*, 16(12): 0260960.

Bahrami-Rad, S. and R. Hajiboland. 2017. Effect of potassium application in drought-stressed tobacco (*Nicotiana rustica* L.) plants: Comparison of root with foliar application. *Ann. Agri. Sci.*, 62(2): 121-130.

Birthal, P.S., J. Hazrana, D.S. Negi and G. Pandey. 2021. Benefits of irrigation against heat stress in agriculture: evidence from wheat crop in India. *Agri. Water Manag.*, 255: 106950.

Bremner, J.M. 1965. Total nitrogen. Methods of soil analysis: Part 2 chemical and microbiological properties, 9: 1149-1178.

Coolong, T. 2013. Using irrigation to manage weeds: A focus on drip irrigation. Intech: Agricultural and Biological Sciences," Weed and Pest Control-Conventional and New Challenges", book edited by Sonia Soloneski and Marcelo Larramendy, 161-179.

Fanaei, H.R., H. Akbarimoghaddam and M. Narouyirad. 2012. Evaluation response of different genotypes of spring canola to water deficit. *Int. Res. J. Appl. Basic Sci*., 3: 2327-2332.

Farouk, S. and A.R. Amany. 2012. Improving growth and yield of cowpea by foliar application of chitosan under water stress. *Egyp. J. Biol.*, 14: 14-16.

García-Hernández, G., R. Araujo-Díaz, G. Estrada-Campuzano, C.G. Martínez-Rueda and A. Domínguez-López. 2022. Physiological and numerical components of canola yield affected by density and sowing system. *Revista Mexicana de Ciencias Agrícolas*, 13(4): 661-673.

Ghosh, P.K., K.M. Hati, K.G. Mandal, A.K. Misra, R.S. Chaudhary and K.K. Bandyopadhyay. 2000. Sulphur nutrition in oilseeds and oilseed-based cropping systems. *Fert. News*, 45(8): 27-40.

Gueta-Dahan, Y., Z. Yaniv, B.A. Zilinskas and G. Ben-Hayyim. 1997. Salt and oxidative stress: similar and specific responses and their relation to salt tolerance in citrus. *Planta*, 203: 460-469.

Hussain, R.A., R. Ahmad, F. Nawaz, M.Y. Ashraf and E.A. Waraich. 2016. Foliar NK application mitigates drought effects in sunflower (*Helianthus annuus* L.). *Acta Physiol. Plant.,* 38: 1-14.

Hussain, S. and M.N. Shah. 2023. Organic amendments mitigate drought stress-induced oxidative changes in synthetic cultivars of maize. *Pak. J. Bot.*, 55(2): 429-436.

Janero, D.R., 1990. Malondialdehyde and thiobarbituric acid-reactivity as diagnostic indices of lipid peroxidation and peroxidative tissue injury. *Free Rad. Biol. Med.*, 9(6): 515-540.

Johnson, R., K. Vishwakarma, M.S. Hossen, V. Kumar, A.M. Shackira, J.T. Puthur, G. Abdi, M. Sarraf and M. Hasanuzzaman. 2022. Potassium in plants: Growth regulation, signaling, and environmental stress tolerance. *Plant Physiol. Biochem.*, 172: 56-69.

Karthika, K.S., I. Rashmi and M.S. Parvathi. 2018. Biological functions, uptake and transport of essential nutrients in relation to plant growth. *Plant Nutr. Abiotic Stress Toler.*, 1-49.

Katuwal, K.B., Y. Cho, S. Singh, S.V. Angadi, S. Begna and M. Stamm. 2020. Soil water extraction pattern and water use efficiency of spring canola under growth-stage-based irrigation management. *Agri. Water Manag.*, 239: 106232.

Kumar, K.B. and P.A. Khan. 1982. Peroxidase & polyphenol oxidase in excised ragi (*Eleusine coracana* CV PR 202) leaves during senescence.

Lang, Y., M. Wang, J. Xia and Q. Zhao. 2018. Effects of soil drought stress on photosynthetic gas exchange traits and chlorophyll fluorescence in Forsythia suspensa. *J. Forest. Res.*, 29: 45-53.

Majeed, S., F. Nawaz, M. Naeem and M.Y. Ashraf. 2018. Effect of exogenous nitric oxide on sulfur and nitrate assimilation pathway enzymes in maize (*Zea mays* L.) under drought stress. *Acta Physiol. Plant.*, 40(12): 206.

Malekpoor, F., A.G. Pirbalouti and A. Salimi. 2016. Effect of foliar application of chitosan on morphological and physiological characteristics of basil under reduced irrigation. *Res. Crops*, 17(2): 354-359.

Mohtashami, R., M.M. Dehnavi, H. Balouchi and H. Faraji. 2020. Improving yield, oil content and water productivity of dryland canola by supplementary irrigation and selenium spraying. *Agri. Water Manag.*, 232: 106046.

Mosse, J. 1990. Nitrogen-to-protein conversion factor for ten cereals and six legumes or oilseeds. A reappraisal of its definition and determination. Variation according to species and to seed protein content. *J. Agri. Food Chem.*, 38(1): 18-24.

Mostofa, M.G., M.M. Rahman, T.K. Ghosh, A.H. Kabir, M. Abdelrahman, M.A.R. Khan, K. Mochida and L.S.P. Tran. 2022. Potassium in plant physiological adaptation to abiotic stresses. *Plant Physiol. Biochem*., 186: 279-289.

Nagata, M. and I. Yamashita. 1992. Simple method for simultaneous determination of chlorophyll and carotenoids in tomato fruit. *Nippon Shokuhin Kogyo Gakkaishi*, 39(10): 925-928.

Nawaz, F., R. Ahmad, M.Y. Ashraf, E.A. Waraich and S.Z. Khan. 2015. Effect of selenium foliar spray on physiological and biochemical processes and chemical constituents of wheat under drought stress. *Ecotoxicol. Environ. Safety*, 113: 191-200.

Pal, Y., R.J. Gilkes and M.T.F. Wong. 2001. Soil factors affecting the availability of potassium to plants for Western Australian soils: a glasshouse study. *Soil Res.*, 39(3): 611-625.

Pimstein, A., A. Karnieli, S.K. Bansal and D.J. Bonfil. 2011. Exploring remotely sensed technologies for monitoring wheat potassium and phosphorus using field spectroscopy. *Field Crops Res.*, 121(1): 125-135.

Rathje, 1959. Jackson, ML: Soil chemical analysis. Verlag: Prentice Hall, Inc., Englewood Cliffs, NJ. 1958, 498 S. DM 39.40.

Reddy, A.R., K.V. Chaitanya and M. Vivekanandan. 2004. Drought-induced responses of photosynthesis and antioxidant metabolism in higher plants. *J. Plant Physiol.*, 161(11): 1189-1202.

Rezaei, R., S.A.R. Valadabadi, A.S. Rad, S. Sayfzadeh and E.H. Masouleh. 2018. Effects of biological fertilizers application and various amounts of urea fertilizers under water stress conditions on yield, nitrogen use efficiency and effective ingredients of *Calendula officinalis* L. *Iran. J. Med. Arom. Plants*, 34(4): Fa547-Fa563.

Salami, M. and S. Saadat. 2013. Study of potassium and nitrogen fertilizer levels on the yield of sugar beet in jolge cultivar. *J. Novel Appl. Sci*., 2(4): 94-100.

Saleem, M.A., A. Shehzad, A. Ahad, M. Idrees, M. Sajjad, N. Iqbal and W. Akram. 2022. Comparative performances of wheat lines under different irrigation regimes. *Plant Cell Biotech. Mol. Biol.*, 23(31-32), 67-77.

Saleem, M.A., M. Tahir, T. Ahmad and M.N. Tahir. 2020. Foliar application of boron improved the yield and quality of wheat (*Triticum aestivum* L.) in a calcareous field. *Soil & Environ.,* 39(1): 59-66.

Sardans, J. and J. Peñuelas. 2021. Potassium control of plant functions: Ecological and agricultural implications. *Plants*, 10(2): 419.

Shabbir, R.N., E.A. Waraich, H. Ali, F. Nawaz, M.Y. Ashraf, R. Ahmad, M.I. Awan, S. Ahmad, M. Irfan, S. Hussain and Z. Ahmad. 2016. Supplemental exogenous NPK application alters biochemical processes to improve yield and drought tolerance in wheat (*Triticum aestivum* L.). *Environ. Sci. Pollut. Res.*, 23: 2651-2662.

Shafiq, F., H. Batool, S.H. Raza and M. Hameed. 2015. Effect of potassium nitrate seed priming on allometry of drought-stressed cotton (*Gossypium hirsutum* L.). *J. Crop Sci. Biotechnol.*, 18: 195-204.

Shah, M.N., D.L. Wright, S. Hussain, S.D. Koutroubas, R. Seepaul, S. George, S. Ali, M. Naveed, M. Khan, M.T. Altaf and K. Ghaffor. 2023. Organic fertilizer sources improve the yield and quality attributes of maize (*Zea mays* L.) hybrids by improving soil properties and nutrient uptake under drought stress. *J. King Saud Uni. Sci.*, 35(4): 102570.

Singh, B.K., S.R. Sharma and B. Singh. 2010. Antioxidant enzymes in cabbage: variability and inheritance of superoxide dismutase, peroxidase and catalase. *Sci. Hort.*, 124(1): 9-13.

Steel, R.G. and J.H. Torrie. 1996. Principles and procedures of statistics: a biometrical approach. New York, NY, USA: McGraw-Hill.

Süzer, S., 2015. Effects of plant nutrition on canola (*Brassica napus* L.) growth. *Trakya Univ. J. Nat. Sci.*, 16(2): 87-90.

Tammam, A.A., M.F.A. Alhamd and M.M. Hemeda. 2008. Study of salt tolerance in wheat (*Triticum aestium* L.) cultivar Banysoif 1. *Aust. J. Crop Sci.*, 1(3): 115-125.

Tetteh, E.T., J.P. de Koff, B. Pokharel, R. Link and C. Robbins. 2019. Effect of winter canola cultivar on seed yield, oil, and protein content. *Agron. J.*, 111(6): 2811-2820.

Wada, S., D. Takagi, C. Miyake, A. Makino and Y. Suzuki, 2019. Responses of the photosynthetic electron transport reactions stimulate the oxidation of the reaction center chlorophyll of photosystem I, P700, under drought and high temperatures in rice. *Int. J. Mol. Sci.*, 20(9): 2068.

Waraich, E.A., R. Ahmad, M.Y. Ashraf, Saifullah and M. Ahmad. 2011. Improving agricultural water use efficiency by nutrient management in crop plants. *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science*, 61(4): 291-304.

Zhang, Y., Z. Li, Y.P. Li, X.Q. Zhang, X. Ma, L.K. Huang, Y.H. Yan and Y. Peng. 2018. Chitosan and spermine enhance drought resistance in white clover, associated with changes in endogenous phytohormones and polyamines, and antioxidant metabolism. *Fun. Plant Biol.*, 45(12): 1205-1222.