Potassium fertilization improves growth, yield and seed quality of sunflower (*Helianthus annuus* L.) under drought stress at different growth stages

Javed Shabbir Dar¹, Mumtaz Akhtar Cheema², Muhammad Ishaq Asif Rehmani³*, Shahnwarz Khuhrò⁴, Shahjahan Rajput⁴, Ahmad Latif Virk⁵, Sajid Hussain⁶, Muhammad Amjad Bashir⁷, Suliman M. Alghanem⁸, Fahad Mohammed Al-Zuaibr⁹, Mohammad Javed Ansari⁸, Kamel Hessini¹⁰

1 Department of Agronomy, SZABAC Dokri, Larkana, Pakistan, 2 School of Science and the Environment, Memorial University of Newfoundland, Corner Brook, Newfoundland and Labrador, Canada, 3 Department of Agronomy, Ghazi University, Dera Ghazi Khan, Pakistan, 4 Department of Entomology, SZABAC Dokri, Larkana, Pakistan, 5 College of Agronomy and Biotecnology, China Agricultural University, Beijing, China, 6 Institute of Hydrobiology, Chinese Academy of Science, Wuhan, China, 7 Department of Plant Protection Faculty of Agricultural Sciences, Ghazi University, Dera Ghazi Khan Punjab, Pakistan, 8 Department of Biology Faculty of Science, Tabuk University, Tabuk, Saudi Arabia, 9 Department of Botany, Hindu College Moradabad (Mahatma Jyotiba Phule Rohilkhand University Bareilly), Moradabad, India, 10 Department of Biology, College of Sciences, Taif University, Taif, Saudi Arabia

* amjadhajbani@gmail.com, mrehmani@gudgk.edu.pk

Abstract

Water scarcity is a major concern for sunflower production in the semi-arid and arid regions of the world. Potassium (K) application has been found effective to alleviate the influence of drought stress; however, the impact of drought stress on seed quality of sunflower has not been reported frequently. Therefore, a field experiment was performed to determine the optimum K requirement for mitigating the adverse effects of water stress and improving growth and seed quality of spring-planted sunflower. Sunflower plants were exposed to water stress at different growth stages, i.e., I₁ = no stress (normal irrigation), I₂ = pre-anthesis stress (irrigation skipped at pre-anthesis stage), I₃ = anthesis stress (irrigation skipped at anthesis stage) and I₄ = post-anthesis stress (irrigation skipped at post-anthesis stage). Potassium was applied at four different rates, i.e., K₀ = 0, K₁ = 50, K₂ = 100 and K₃ = 150 kg ha⁻¹. The results revealed that water stress at pre- and post-anthesis stages significantly reduced plant height, head diameter, number of achenes, oleic acid contents, and phosphorus (P) uptake. However, pre-anthesis stress improved linoleic acid contents. Treatment I₄K₃ (stress-free with 150 kg ha⁻¹ K) was optimum combination for 1000-achene weight, biological and achene yields, oil contents, protein contents, and N and P uptake. Results indicated that a higher amount of K and irrigation resulted in higher yield, whereas yield and yield components decreased with early-stage water stress. Nevertheless, potassium application lowered the impacts of waters stress compared to no application. Keeping in view these results, it is recommended that sunflower must be supplied 150 kg ha⁻¹ K in arid and semi-arid regions to achieve higher yield and better seed quality.
Introduction

Suitable soil conditions, including adequate water and nutrient supply are required for optimum crop growth and yield [1–4]. Water is critical for plant metabolism at all growth stages; therefore, water stress is one of the most limiting factors for crop production in semi-arid and arid regions [5–7]. However, the impact of water stress varies depending upon the intensity and duration of stress, plant species, crop growth stage, and management practices. Certain crop growth stages (pre-anthesis, anthesis, and post-anthesis) could be more sensitive to water shortage [8–10]. Drought stress impairs protein and nucleic acid synthesis, photosynthesis and respiration, and reduces yield [10, 11]. Sunflower (Helianthus annuus L.) is moderately drought tolerant and successfully grows in diversified agro-climatic conditions. Sunflower has shown a positive response to irrigation in terms of growth and yield in regions with inadequate precipitation and low soil water supply [12]. Timely and judicious irrigation management, especially at critical growth stages significantly improves yield in sunflower. During its initial growth (30 days after sowing) sunflower crop merely uses 20–25% of its total crop water requirement. However, at the reproductive stage, plant requires more water, and onset of water stress can cause substantial yield losses [13, 14]. Anthesis and seed development are the most critical growth stages of sunflower to drought stress [12, 15].

Fertilizers are one of the basic inputs of agriculture and their timely availability is crucial for agricultural production [16–20]. After the introduction of high-yielding cultivars, a rapid decline has been recorded in soil nutrient status. High-yielding varieties/hybrids require higher amount of nutrients for rapid growth and high biomass accumulation [21–23]. Among macro-nutrients, potassium (K) is an essential nutrient and plays a key roles in improving crop yield and quality of the produce [15, 24]. Moreover, it strengthens crop plants by imparting resistance against drought, salinity, higher temperature, other abiotic stress, and biotic stresses including pests and diseases [4, 25–27]. Potassium contributes to the osmotic pull that draws water into plant roots; therefore, its deficiency in plants makes them susceptible to water shortage, mainly due to inability to use available water [24, 28, 29].

Local production of edible oil in Pakistan is insufficient to meet the rising demands of rapidly growing population [30]. The unprecedented rate of population increase and urbanization, further widens the gap between domestic oil production and demand. Swift increase in domestic oilseed production has been the key target for economic and agricultural policymakers due to escalating import bills [31]. A wide gap is present regarding fertilizer management and irrigation requirements of sunflower crop for high seed production, better quality, and vigorous growth. Therefore, this study was conducted to assess the drought susceptibility of sunflower at different crop growth stages and mitigate drought-induced yield and quality losses by potassium application in spring-planted sunflower under semi-arid agro-climatic conditions. It was hypothesized that potassium supplementation will lower the adverse effects of drought stress on yield and seed quality of sunflower. It was further hypothesized that different growth stages will also differ in their sensitivity to drought stress. The results would help to improve the yield and seed quality of sunflower in drought-prone arid and semi-arid regions.

Materials and methods

Site and soil

Field experiments were performed at Agronomic Research Area, Department of Agronomy, University of Agriculture, Faisalabad, Pakistan (31.25°N, 73.09°E, and 183 m a.s.l.). The soil of research area is well-drained, sandy-clay-loam in texture (sand:silt:clay 54:24:22%) with 1.99 dSm⁻¹ EC, low organic matter (1.04%), slightly alkaline (pH 8.1) with 143 and 6.24 ppm
available K and P, respectively. Weather data of the experimental site during experiment was collected from Agrometeorological Unit, located at 150 m distance form the experimental site (Table 1).

### Experimental design and treatments

Experimental treatments were arranged in randomized complete block design with split-plot arrangement with a net plot size of 3.6 m \( \times \) 7.0 m and three replications. Four water stress regimes \( [I_0 = \text{control (normal irrigations)}, I_2 = \text{water stress at pre-anthesis stage (R3)}, I_3 = \text{water stress at anthesis stage (R5.5, 50\% of the capitulum in anthesis)}, \text{and } I_4 = \text{water stress at post-anthesis stage (R7)}] \) were kept in main plots, whereas potassium application rates \( [0 (K_0), 50 (K_1), 100 (K_2) \text{ and } 150 (K_3) \text{ kg ha}^{-1}] \) were randomized in sub-plots. Sub-plots were separated by buffer zones to avoid seepage across other experimental plots.

### Crop husbandry

Before sowing, the experimental area was thoroughly irrigated, and seedbed was prepared by cultivating the soil twice, using a tractor-mounted cultivator, followed by leveling. Seeds of sunflower hybrid (‘S-278’, 3 seeds hill\(^{-1}\)) were sown (10 kg ha\(^{-1}\)) on February 14\(^{th}\) 2015 (season-I) and February 16\(^{th}\), 2016 (season-II) using a dibbler keeping 60 \( \times \) 25 cm row \( \times \) hill spacing. One plant hill \(^{-1}\) was maintained two weeks after emergence [10]. Half of the N [75 kg N ha\(^{-1}\) as urea and diammonium phosphate (DAP)] along with a full dose of phosphorous [100 kg P\(_2\)O\(_5\) ha\(^{-1}\) as DAP] and potash [according to treatment, as sulfate of potash (SOP)] were soil incorporated as basal dose. The remaining nitrogen [75 kg N ha\(^{-1}\) as urea] was top-dressed at first irrigation. All agronomic practices, except K application and irrigation skipping were kept normal and uniform following local recommendations of plant protection measures to keep the crop free from diseases, insect pests, and weeds.

### Irrigation methodology

Crop was irrigated according to treatments using a siphon tube (length = 5 m, diameter = 7.62 cm). Timing and quantity of irrigation water application were calculated using the formula described earlier [32].

\[
T = \frac{A \times d}{Q}
\]

Where \( t \) denotes the time (h) of irrigation, \( A \) is field area (m\(^2\)), \( d \) is depth (mm) of irrigation water applied and \( Q \) volume of water discharged per unit time (m\(^3\) sec\(^{-1}\)).

Six siphon tubes were calibrated and shifted to different plots. A water control barrier was prepared at cross-channel area to control water flow. Time measurement was done with the help of a stopwatch and at a measured time (two siphon tubes take 5 min and 15 sec. for the discharge of 630 L of water) siphons were shifted to the other field.

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**Table 1. Monthly mean weather data for the growing season of the study during growing seasons.**

|                | Max temp (˚C) | Min. temp (˚C) | Mean. temp (˚C) | Rainfall (mm) | Relative humidity (%) | ET\(_0\) (mm) |
|----------------|---------------|----------------|-----------------|---------------|-----------------------|--------------|
|                | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season |
| February       | 20.1          | 27.6           | 9.8             | 13.1          | 14.9                  | 20.3         | 35.1          | 14.6          | 67.7          | 52.36      | 1.7        | 2.7 |
| March          | 27.8          | 28.2           | 15.3            | 14.6          | 21.6                  | 21.4         | 48.6          | 37.1          | 40.8          | 40.7       | 2.8        | 3.2 |
| April          | 35.1          | 37.7           | 18.2            | 20.7          | 26.7                  | 29.2         | 10.8          | 0             | 35.5          | 23.4       | 5.7        | 7.1 |
| May            | 38.1          | 42.3           | 23.4            | 27.3          | 30.8                  | 34.8         | 18.4          | 24.1          | 31.7          | 23.9       | 7.2        | 8.1 |
| June           | 43.3          | 40.3           | 28.7            | 27.1          | 36.1                  | 33.7         | 62.5          | 55.6          | 32.5          | 26.2       | 8.7        | 7.9 |

https://doi.org/10.1371/journal.pone.0256075.t001

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Growth, yield and seed quality response of sunflower (Helianthus annuus L.) with potassium fertilization
Measurements

Ten plants were randomly selected from each experimental unit, marked for the assessment of growth stages and used for measurement of plant height, head diameter, number of achenes head$^{-1}$ and 1000-achene weight. The collected data were averaged for different treatments [29]. The plant population was counted at harvest. Plant height (cm) was measured by using measuring rod, from ground level to the base of capitulum. Subsequently, same plants were used for the measurement of head diameter (cm) using measuring tape. At harvest maturity, three rows (from each experimental unit) were manually harvested and crop samples were sun-dried. The weight of plants from each plot was recorded for biological yield [3]. For achene yield heads were separated and threshed manually to calculate seed yield from each experimental plot subsequently converted to hectare basis [10].

Leaf area of six randomly selected plants per experimental plot was measured by using leaf area meter (Licor, Model 3100). Ratio of leaf area to the land area was used to calculate the leaf area index (LAI) [19]. Net assimilation rate (NAR) and crop growth rate (CGR) were estimated following [33] as described earlier [34].

\[
NAR = \frac{W_2-W_1}{T_2-T_1} \times \frac{\ln LA_2 - \ln LA_1}{LA_2 - LA_1}
\]

Where NAR is net assimilation rate (g cm$^{-2}$ day$^{-1}$). The $W_1$ and $W_2$ are crop dry weights at first and second observation. $T_2-T_1$ is time difference between first and second observation. $LA_2-LA_1$ is difference in leaf area between two observations. The $\ln$ is natural logarithm.

\[
CGR = \frac{W_2-W_1}{T_2-T_1}
\]

Where CGR is crop growth rate (g m$^{-2}$ day$^{-1}$). The $W_1$ and $W_2$ are crop dry weights at first and second observation. $T_2-T_1$ is time difference between first and second observation.

Achene oil and protein contents (%)

Soxhlet fat extraction method was used to determine seed oil contents by random selection of samples from the experimental units [35]. Protein contents of achenes were determined as an average of one sample from each replication by using micro-Kjeldahl method [35].

Achene-fatty acid profile (%)

Fatty acid composition was determined using Shamadzo Gas Liquid Chromatograph (GLC), Model CS-7 with a glass column (2.1 m × 3.2 mm) packed with 3% SP2310/2% / SP2300 coated chromosorb WAW on 100/120 mesh. For the analysis, the column oven was operated at 230˚C. Methylating solution (4 g metallic sodium) was used for preparing methyl esters of oil.

Nutrient uptake

Collected plant samples (n = 144) were oven-dried (72˚C to constant weight), ground using an electric grinding machine and stored in clean dry plastic bags for chemical analysis. The nitrogen contents of achenes and stalk (including stem, leaf, and head) were determined following micro-Kjeldahl method [35].

Oven-dried plant materials (1 g) were digested in the di-acid mixture (10 ml of 72% HClO$_4$ + 20 ml concentrated HNO$_3$) and subsequently cooled. The digest was transferred to a 100 ml volumetric flask to make volume with distilled water. Phosphorus concentration was observed on a spectrophotometer at 410 nm. For potassium, an aliquot from the digested material was
taken to determine K$^+$ using a flame photometer (Jenway PFP-7 Flame Photometer) equipped with a K$^+$ filter (Method 58a). Phosphorus and potassium concentrations (%) in plant samples were calculated using a standard curve and then converted in plant uptake by multiply with yield.

**Statistical analysis**

Collected data were statistically analyzed using MSTAT-C [36]. The overall significance of the data was evaluated using analysis of variance (ANOVA), treatment means were compared through the least significant difference (LSD) test at the 0.05 level.

**Results**

Water stress at different growth stages and potassium fertilizer levels significantly influenced various growth, yield and quality parameters of sunflower. Skipping irrigation at different crop growth produced a significant effect on crop yield. Yield reduction depends on the degree of plant water stress at critical growth stages. Limited water supply is frequently associated with yield reduction. Both water stress and potassium application significantly affected head diameter and number of achenes (Table 2). Plant height was significantly affected by water stress; however, different level of potassium had no effect in this regard (Table 2). The tallest plants were recorded from normal irrigation, while the shortest plants were recorded from pre-anthesis stress. There was a non-significant effect of water stress and potassium application levels on plant population.

Head diameter and number of achene head$^{-1}$ were significantly affected by water stress and potassium levels. Normal irrigation produced the highest number of achene head$^{-1}$ and head diameter, while pre-anthesis stress resulted in the lowest head diameter and number of achene head$^{-1}$. Treatment K$_3$ observed the highest head diameter and number of achenes head$^{-1}$ and these results were statistically at par with K$_2$. Treatments K$_0$ and K$_1$ had statistically similar results, while the lowest values were recorded for K$_0$.

Major yield parameters, i.e., 1000-achene weight, achene yield, and biological yield were significantly affected by the interactions among water stress and potassium application, while had non-significant effect on harvest index (Table 3). Treatment I$_0$K$_3$ was optimum and resulted in the highest 1000-achene weight, achene yield, and biological yield during both years.

The highest LAI was recorded on 75 DAS. Water stress significantly decreased LAI (75 DAS), while potassium application had no effect in this regard. The lowest LAI was recorded for pre-anthesis stress. During 2015, the highest LAI was recorded from I$_3$ and these results were statistically similar with I$_0$. During 2016, the highest values were observed from I$_0$ (Fig 1).

In the fatty acid profile, stearic acid and palmitic acid were not affected by water stress (Table 4). Stearic acid was significantly influenced by potassium application. Treatment K$_2$ observed the highest stearic acid contents and these results are statistically similar to K$_3$ during both years. The highest linoleic acid was observed under pre-anthesis stress during both years. The lowest values of linoleic acid contents were observed for normal irrigation. Linoleic acid contents were slightly changed with increasing potassium application. Only K$_3$ showed statistically significant results as compared to all other treatments. Water stress significantly reduced oleic acid contents during both years.

Interactive effect of water stress and potassium application significantly influenced N and K uptake (Table 5). Treatment I$_0$K$_3$ resulted in the highest uptake of N and K in the plants against the lowest in I$_1$K$_0$. The highest P uptake was recorded from no stress against the minimum in pre-anthesis stress (Table 5).
The highest crop growth rate was recorded from I₀ during 2015 (Table 6), whereas I₀ and I₃ show statistically similar results during 2016. The lowest LAI was recorded from I₁ during both the years. Treatments K₀ and K₃ observed the lowest and the highest crop growth rate, respectively. Net assimilation rate (NAR) showed a different pattern than other parameters. The highest NAR was recorded for I₁. Remaining treatments were statistically similar. However, different potassium levels were statistically similar for NAR. Interactive effect of water stress and K application significantly influenced achene oil and protein contents. The highest oil and protein contents were recorded from I₀K₃ during both years. Treatment I₁K₀ produced the minimum oil and protein contents during both years (Table 6). Increasing K application significantly improved P uptake. Higher rates of K (K₃) resulted in better P uptake during both years. Correlation coefficients between achene yield and yield components showed a significant and positive correlation during 2015 and 2016 (Table 7).

### Table 2. Effect of water stress at different growth stages and potassium application on agronomic traits and yield components of sunflower.

| Treatments | Plant population (m⁻²) | Plant height (cm) | Head diameter (cm) | No. of achenes head⁻¹ | W × K |
|------------|------------------------|-------------------|-------------------|------------------------|-------------------|
|            | 1st season             | 2nd season        | 1st season        | 2nd season             | 1st season        | 2nd season |
|            |                        |                   |                   |                        |                   |            |
| Water stress (W) |                   |                   |                   |                        |                   |            |
| I₀         | 166.75                 | 167.00            | 164.47 a          | 161.67 a               | 20.09 a           | 19.48 a    | 1062 a  | 1026 a |
| I₁         | 166.50                 | 166.50            | 147.24 d          | 144.87 d               | 15.57 d           | 15.09 d    | 865 d   | 845 d  |
| I₂         | 166.50                 | 166.42            | 156.82 c          | 153.20 c               | 16.04 c           | 15.78 c    | 935 c   | 906 c  |
| I₃         | 166.92                 | 166.50            | 162.04 b          | 156.02 b               | 18.11 b           | 17.48 b    | 1004 b  | 974 b  |
| LSD        | ns                     | ns                | 1.71              | 0.28                   | 0.29              | 43         | 41      |

| Potassium application levels (K) |                   |                   |                   |                        |                   |            |
| K₀         | 166.83                 | 166.75            | 156.97            | 153.28                 | 16.70 b           | 16.24 b    | 937 b   | 905 b  |
| K₁         | 167.00                 | 166.42            | 157.59            | 153.89                 | 16.75 b           | 16.29 b    | 949 b   | 918 b  |
| K₂         | 166.58                 | 166.50            | 158.28            | 154.56                 | 18.06 a           | 17.53 a    | 986 a   | 959 a  |
| K₃         | 166.25                 | 167.00            | 157.71            | 154.02                 | 18.31 a           | 17.77 a    | 993 a   | 970 a  |
| LSD        | ns                     | ns                | ns                | ns                     | 0.42              | 0.40       | 33      | 32     |

_0 = no stress, _1 = pre anthesis stress, _2 = anthesis stress, _3 = post anthesis stress, K₀ = 0 kg K ha⁻¹, K₁ = 50 kg K ha⁻¹, K₂ = 100 kg K ha⁻¹, K₃ = 150 kg K ha⁻¹, LSD = least significant difference, ns = non-significant, Mean values sharing the same letter in a column do not differ significantly at P = 0.05.

https://doi.org/10.1371/journal.pone.0256075.t002
Discussion

Water stress at different crop growth stages significantly decreased yield and yield attributes. Plant height, head diameter, number of achenes and 1000-achene weight were closely related to achene yield. Severe yield reduction in pre-anthesis stress during the spring season is primarily due to high evaporative demands.

Yield and yield components were reduced by water stress at critical stages, especially at pre-anthesis and anthesis. However, post-anthesis water stress caused less yield reduction. Pre-anthesis and anthesis stress reduce yield potential because available water at these stages is insufficient during canopy formation and reproductive development.

Better performance of sunflower in terms of yield and yield components under higher K fertilization is due to the involvement of K in main osmotic solute of plants [28, 37]. Potassium accumulation at the cellular level results in osmotic water uptake and generation of cell turgor

Table 3. Effect of water stress at different growth stages and potassium application on 1000 achene weight, achene yield, biological yield and harvest index.

| Treatments | 1000-achene weight (g) | Achene yield (kg ha\(^{-1}\)) | Biological yield (kg ha\(^{-1}\)) | Harvest index |
|------------|------------------------|-------------------------------|-----------------------------------|--------------|
|            | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season |
| Water stress (W) | | | | | | | | |
| I\(_0\) | 55.85 a | 54.32 a | 2997 a | 2921 a | 8311 a | 8409 a | 36.05 a | 34.72 a |
| I\(_1\) | 48.44 d | 47.15 d | 2268 d | 2184 d | 7145 d | 7054 d | 31.75 d | 30.97 d |
| I\(_2\) | 50.28 c | 48.94 c | 2548 c | 2467 c | 7685 c | 7605 c | 33.15 c | 32.44 c |
| I\(_3\) | 52.24 b | 50.72 b | 2718 b | 2635 b | 7882 b | 7936 b | 34.49 b | 33.20 b |
| LSD | 0.90 | 0.74 | 43 | 47 | 95 | 150 | 0.69 | 0.70 |
| Potassium application levels (K) | | | | | | | | |
| K\(_0\) | 49.92 d | 48.39 d | 2541 d | 2460 d | 7688 b | 7656 b | 32.97 d | 32.05 c |
| K\(_1\) | 51.14 c | 49.71 c | 2589 c | 2511 c | 7695 b | 7694 b | 33.58 c | 32.56 b |
| K\(_2\) | 52.55 b | 51.20 b | 2684 b | 2601 b | 7841 a | 7826 a | 34.14 b | 33.16 a |
| K\(_3\) | 53.21 a | 51.84 a | 2718 a | 2635 a | 7798 a | 7832 a | 34.76 a | 33.55 a |
| LSD | 0.47 | 0.47 | 32 | 31 | 78 | 59 | 0.36 | 0.40 |

I\(_0\) = no stress, I\(_1\) = pre anthesis stress, I\(_2\) = anthesis stress, I\(_3\) = post anthesis stress, K\(_0\) = 0 kg K ha\(^{-1}\), K\(_1\) = 50 kg K ha\(^{-1}\), K\(_2\) = 100 kg K ha\(^{-1}\), K\(_3\) = 150 kg K ha\(^{-1}\), LSD = least significant difference, ns = non-significant, Mean values sharing the same letter in a column do not differ significantly at P = 0.05.

https://doi.org/10.1371/journal.pone.0256075.t003

https://doi.org/10.1371/journal.pone.0256075:1003
needed for stomatal opening and plant growth [38, 39]. Potassium influx inside the stomatal guard cells cause water accumulation leading to their swelling and subsequent stomatal opening, allowing CO\textsubscript{2} and transpired water vapors to move freely in and out of plant tissues. Under water stress, potassium efflux from guard cells and the pores close tightly to prevent water loss. In case of inadequate supply of K, the stomatal activity becomes slow and water losses are high. However, adequate K supply increases plant uptake of water as well as improves its use efficiency within the plant [39–41].

High K application increases leaf water content and lead to K accumulation in the vacuoles, causing stomatal uptake of water, resulting in higher cell turgor and growing cells, induces cell

![Graph](https://doi.org/10.1371/journal.pone.0256075.g001)
elongation and decreases stomatal density. It reduces daily accumulated transpiration water loss from leaves and makes the bulk leaf water relations favorable [42]. Increased K requirement in plants is due to its involvement in regulating photosynthetic \( \text{CO}_2 \) fixation. Drought-induced impaired stomatal movement results in reduced \( \text{CO}_2 \) fixation. Increasing severity of water stress leads to higher K demand to regulate photosynthesis and protect chloroplast against oxidative damage. Drought-induced yield reduction is greatly mitigated by increasing K fertilization [15, 42–44].

Leaf area index is the major component directly related to plant growth and yield. Reduction in leaf growth decreases biomass of all other plant components. The better yields were associated primarily with the presence of more leaf area during early seed development [45].

Water stress at critical stages significantly influences sunflower growth, yield attributes, and achene quality [46, 47].

Table 4. Effect of water stress at different growth stages and potassium application on fatty acid profile.

| Treatments | Stearic acid (%) | Palmitic acid (%) | Linoleic acid (%) | Oleic acid (%) |
|------------|-----------------|------------------|------------------|---------------|
|            | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season | 1\(^{st}\) season | 2\(^{nd}\) season |
| Water stress (W) |                 |                  |                  |               |
| \(I_0\)    | 2.04            | 1.96             | 6.05             | 5.97          | 58.94 d      | 56.89 c      | 29.89 a      | 31.06 a      |
| \(I_1\)    | 2.01            | 1.95             | 6.00             | 5.91          | 62.56 a      | 60.27 a      | 27.71 c      | 28.56 c      |
| \(I_2\)    | 2.03            | 1.97             | 6.08             | 6.00          | 61.41 b      | 58.73 b      | 28.94 b      | 30.02 b      |
| \(I_3\)    | 2.02            | 1.96             | 6.12             | 6.01          | 59.98 c      | 57.69 c      | 29.15 b      | 30.09 b      |
| LSD        | ns              | ns               | ns               | ns            | 0.61         | 0.88         | 0.66         | 0.54         |

Potassium application levels (K) |            |                  |                  |               |
| \(K_0\)    | 1.99 b          | 1.92 b           | 6.04             | 5.98          | 60.10 b      | 57.76 c      | 28.04 c      | 28.81 c      |
| \(K_1\)    | 1.97 b          | 1.90 b           | 6.11             | 5.94          | 60.49 b      | 57.98 bc     | 28.61 bc     | 29.74 b      |
| \(K_2\)    | 2.00 a          | 2.02 a           | 6.03             | 6.01          | 60.63 b      | 58.53 b      | 29.11 b      | 30.20 b      |
| \(K_3\)    | 2.05 a          | 2.00 a           | 6.06             | 5.97          | 61.66 a      | 59.32 a      | 29.93 a      | 30.99 a      |
| LSD        | 0.04            | 0.04             | ns               | ns            | 0.55         | 0.59         | 0.65         | 0.74         |

\(I_0\) = no stress, \(I_1\) = pre anthesis stress, \(I_2\) = anthesis stress, \(I_3\) = post anthesis stress, \(K_0\) = 0 kg K ha\(^{-1}\), \(K_1\) = 50 kg K ha\(^{-1}\), \(K_2\) = 100 kg K ha\(^{-1}\), \(K_3\) = 150 kg K ha\(^{-1}\), LSD = least significant difference, ns = non-significant, Mean values sharing the same letter in a column do not differ significantly at \(P = 0.05\)

https://doi.org/10.1371/journal.pone.0256075.t004
Like other crops, water deficit experienced during different stages of crop development in sunflower, resulted in compromised CGR, significantly contributing to the yield anomalies [50–53].

Examination of the variation in the content of the four major fatty acids (stearic, palmitic, linoleic, and oleic acid) showed that the oil fatty acid composition at the initial phases of seed formation differed substantially from matured seeds [15, 54]. Oleic and linoleic acid concentrations in oil are significantly affected by growing conditions. Water stress at anthesis and mean temperature probably affected linoleic and oleic acid concentration. However, average linoleic and oleic contents of the oil were not affected by irrigation regimes [15]. Cooler weather can extend the duration of the grain fill period; however, could alter the composition of fatty acids in the oil. Cooler temperature can slow the conversion of linoleic acid fatty acid

| Treatments | N uptake | P uptake | K uptake |
|------------|----------|----------|----------|
|            | 1st Season | 2nd Season | 1st Season | 2nd Season | 1st Season | 2nd Season |
| Water stress (W) |          |          |          |          |          |
| I₀         | 82.59 a   | 81.69 a   | 30.11 a   | 29.24 a   | 131.78 a   | 134.67 a   |
| I₁         | 56.14 d   | 56.31 d   | 17.47 d   | 17.71 d   | 72.43 d    | 74.72 d    |
| I₂         | 65.66 c   | 64.87 c   | 20.50 c   | 20.39 c   | 91.45 c    | 94.46 c    |
| I₃         | 73.92 b   | 72.47 b   | 23.79 b   | 23.63 b   | 105.96 b   | 109.57 b   |
| LSD        | 2.04      | 1.93      | 1.94      | 2.01      | 3.86       | 3.89       |
| Potassium application levels (K) |          |          |          |          |          |
| K₀         | 55.86 d   | 55.64 d   | 18.57 d   | 18.31 d   | 81.52 d    | 83.58 d    |
| K₁         | 63.84 c   | 63.95 c   | 20.71 c   | 20.57 c   | 88.66 c    | 90.89 c    |
| K₂         | 77.93 b   | 76.67 b   | 25.24 b   | 25.09 b   | 111.06 b   | 115.01 b   |
| K₃         | 80.68 a   | 79.06 a   | 27.35 a   | 27.01 a   | 120.37 a   | 123.93 a   |
| LSD        | 1.32      | 1.38      | 1.71      | 1.61      | 4.25       | 4.37       |
| W×K        |          |          |          |          |          |
| I₀K₀       | 66.11 fg  | 66.46 f   | 23.35     | 22.48     | 108.03 ef  | 109.77 e   |
| I₀K₁       | 73.95 e   | 74.46 e   | 26.63     | 25.71     | 112.22 de  | 114.02 e   |
| I₀K₂       | 92.80 b   | 90.96 b   | 34.16     | 33.47     | 145.36 b   | 149.02 b   |
| I₀K₃       | 97.48 a   | 94.90 a   | 36.32     | 35.31     | 161.53 a   | 165.79 a   |
| I₁K₀       | 43.97 l   | 44.75 k   | 14.16     | 14.22     | 62.34 j    | 63.89 l    |
| I₁K₁       | 52.19 k   | 52.47 j   | 15.48     | 15.54     | 64.35 j    | 66.44 l    |
| I₁K₂       | 63.31 hi  | 62.93 gh  | 19.01     | 19.31     | 78.05 hi   | 80.75 gh   |
| I₁K₃       | 65.10 gh  | 65.05 fg  | 21.22     | 21.73     | 84.98 h    | 87.79 g    |
| I₂K₀       | 53.51 k   | 25.90 j   | 15.99     | 16.31     | 74.02 i    | 76.85 h    |
| I₂K₁       | 61.29 ij  | 61.23 h   | 18.34     | 18.49     | 82.14 h    | 85.50 gh   |
| I₂K₂       | 73.61 e   | 72.84 e   | 22.65     | 22.53     | 102.27 fg  | 106.29 ef  |
| I₂K₃       | 74.21 e   | 72.49 e   | 25.01     | 24.24     | 107.36 ef  | 109.19 e   |
| I₃K₀       | 59.84 j   | 58.45 i   | 20.77     | 20.18     | 81.70 hi   | 83.81 gh   |
| I₃K₁       | 67.92 f   | 67.65 f   | 22.36     | 22.56     | 95.92 g    | 97.58 f    |
| I₃K₂       | 81.99 d   | 79.94 d   | 25.16     | 25.04     | 118.58 d   | 123.91 d   |
| I₃K₃       | 85.92 c   | 83.82 c   | 26.84     | 26.72     | 127.63 c   | 132.96 c   |
| LSD        | 2.64      | 2.65      | ns        | ns        | 8.50       | 8.73       |

I₀ = no stress, I₁ = pre anthesis stress, I₂ = anthesis stress, I₃ = post anthesis stress, K₀ = 0 kg K ha⁻¹, K₁ = 50 kg K ha⁻¹, K₂ = 100 kg K ha⁻¹, K₃ = 150 kg K ha⁻¹, LSD = least significant difference, ns = non-significant, Mean values sharing the same letter in a column do not differ significantly at P = 0.05

https://doi.org/10.1371/journal.pone.0256075.t005

[48, 49]. Like other crops, water deficit experienced during different stages of crop development in sunflower, resulted in compromised CGR, significantly contributing to the yield anomalies [50–53].

Examination of the variation in the content of the four major fatty acids (stearic, palmitic, linoleic, and oleic acid) showed that the oil fatty acid composition at the initial phases of seed formation differed substantially from matured seeds [15, 54]. Oleic and linoleic acid concentrations in oil are significantly affected by growing conditions. Water stress at anthesis and mean temperature probably affected linoleic and oleic acid concentration. However, average linoleic and oleic contents of the oil were not affected by irrigation regimes [15]. Cooler weather can extend the duration of the grain fill period; however, could alter the composition of fatty acids in the oil. Cooler temperature can slow the conversion of linoleic acid fatty acid...
to oleic forms in oilseed [55, 56]. Adequate water supply is required during grain filling to achieve high oil concentration [15].

Prevailing temperature during seed development has a key influence on sunflower oil characteristics [57], mainly as a result of synthesis or activation of oleate desaturase at low temperature and its reversible inhibition at elevated temperature [58, 59]. Irrigation may influence the temperature of the vegetative apparatus and the canopy micro-climate [60], increased evapotranspiration cooling of plant tissues after irrigation might have resulted in increased activity of oleate desaturase, causing a lower oleic/linoleic acid ratio [58].

The interaction of N, P, and K is widely discussed in the literature. Potassium application is vital for efficient utilization and resultant synergistic benefits of N and P application [61, 62].

| Treatments | Oil contents (%) | Protein contents (%) | Crop growth rate (CGR) (g m⁻² day⁻¹) | Net assimilation rate (NAR) (g cm⁻² day⁻¹) |
|------------|------------------|----------------------|--------------------------------------|------------------------------------------|
|            | 1st season       | 2nd season           | 1st season                           | 2nd season                               | 1st season                           | 2nd season       |
| Water stress (W) |          |                      |                                      |                                          |                                      |
| I₀         | 42.84 a          | 41.78 a              | 15.61 a                              | 15.24 a                                  | 9.16 a                               | 9.42 a          |
| I₁         | 33.37 d          | 32.60 d              | 13.27 d                              | 12.85 d                                  | 7.57 c                               | 7.76 c          |
| I₂         | 36.70 c          | 36.11 c              | 13.96 c                              | 13.63 c                                  | 8.10 bc                              | 8.58 b          |
| I₃         | 40.09 b          | 38.82 b              | 14.62 b                              | 13.44 b                                  | 8.56 b                               | 9.08 a          |
| LSD        | 0.43             | 0.42                 | 0.44                                 | 0.43                                     | 0.57                                 | 0.45            |

| Potassium application levels (K) |          |                      |                                      |                                          |                                      |
| K₀         | 36.66 d          | 35.77 d              | 13.84 c                              | 13.48 c                                  | 8.16 c                               | 8.48 b          |
| K₁         | 37.10 c          | 36.21 c              | 14.05 c                              | 13.69 c                                  | 8.26 bc                              | 8.59 b          |
| K₂         | 39.31 a          | 38.36 b              | 14.65 b                              | 14.31 b                                  | 8.40 ab                              | 8.85 a          |
| K₃         | 39.93 b          | 38.97 a              | 14.92 a                              | 14.57 a                                  | 8.58 a                               | 8.92 a          |
| LSD        | 0.39             | 0.37                 | 0.26                                 | 0.25                                     | 0.21                                 | 0.24            |

W x K

| I₀K₀ | 40.72 c          | 39.71 c              | 14.71 cd                            | 14.37 cd                                  | 8.76                                 | 9.13            |
| I₀K₁ | 41.21 c          | 40.18 c              | 15.12bc                             | 14.77 bc                                  | 9.06                                 | 9.07            |
| I₀K₂ | 44.09 b          | 43.00 b              | 16.17a                              | 15.79 a                                   | 9.21                                 | 9.52            |
| I₀K₃ | 45.35 a          | 44.22 a              | 16.43 a                             | 16.04 a                                   | 9.62                                 | 9.95            |
| I₁K₀ | 31.87 i          | 31.14 h              | 12.95 i                             | 12.54 i                                   | 7.37                                 | 7.54            |
| I₁K₁ | 32.31 i          | 31.56 h              | 13.04 hi                            | 12.63 hi                                   | 7.63                                 | 7.65            |
| I₁K₂ | 34.39 h          | 33.59 g              | 13.47 gh                            | 13.04 gh                                   | 7.60                                 | 7.97            |
| I₁K₃ | 34.91 gh         | 34.11 fg             | 13.61 fg                            | 13.18 fg                                   | 7.66                                 | 7.90            |
| I₂K₀ | 35.18 fg         | 34.61 ef             | 13.73 efg                           | 13.39 efg                                  | 7.98                                 | 8.34            |
| I₂K₁ | 35.73 f          | 35.15 e              | 13.84 efg                           | 13.50 efg                                  | 8.06                                 | 8.55            |
| I₂K₂ | 37.85 e          | 37.25 d              | 14.08 ef                            | 13.76 e                                   | 8.19                                 | 8.84            |
| I₂K₃ | 38.04 e          | 37.43 d              | 14.21 de                            | 13.88 de                                  | 8.17                                 | 8.57            |
| I₃K₀ | 38.85 d          | 37.62 d              | 13.96 efg                           | 13.64 ef                                   | 8.51                                 | 8.90            |
| I₃K₁ | 39.17 d          | 37.93 d              | 14.19 e                            | 13.87 e                                   | 8.29                                 | 9.09            |
| I₃K₂ | 40.92 c          | 39.62 c              | 14.89 c                            | 14.65 c                                   | 8.58                                 | 9.05            |
| I₃K₃ | 41.43 c          | 40.11 c              | 15.44 b                            | 15.19 b                                   | 8.85                                 | 9.26            |
| LSD    | 0.77             | 0.75                 | 0.51                                | 0.50                                      | ns                                   | ns              |

I₀ = no stress, I₁ = pre anthesis stress, I₂ = anthesis stress, I₃ = post anthesis stress, K₀ = 0 kg K ha⁻¹, K₁ = 50 kg K ha⁻¹, K₂ = 100 kg K ha⁻¹, K₃ = 150 kg K ha⁻¹, LSD = least significant difference, ns = non-significant, Mean values sharing the same letter in a column do not differ significantly at P = 0.05

https://doi.org/10.1371/journal.pone.0256075.t006
The yield response to limited irrigation can be greatest if water is applied to alleviate deficits during critical growth stages of yield formation and proper fertilizer application.

**Conclusion**

Different growth stages of sunflower significantly varied in their response to water stress. Pre-anthesis stage proved highly susceptible to water stress in terms of plant height, head diameter, achene weight, achene yield, biological yield, and harvest index. Similarly, oil and protein contents, crop growth rate, and oleic acid concentration in seed were lowest when water stress was imposed at pre-anthesis stage. Water stress had non-significant effect on stearic acid and palmitic acid concentration. Increasing potassium level had positive effect on the studied parameters, except palmitic acid contents. Increasing potassium fertilizer level significantly helped sunflower plants to recover from water stress. The lowest values of average achene weight, achene yield, biological yield), oil contents, protein contents, uptake of nitrogen, and potassium were recorded for water stress at pre-anthesis stage without potassium application. However, values of these parameters significantly improved with increasing levels of potassium application. Normal irrigation (without stress) treatment combined with higher potassium application (150 kg ha$^{-1}$) resulted in the highest values for growth, yield, and quality attributes. Higher potassium requirement of sunflower during water stress conditions can be the potential reason for these results. Therefore, it concluded that better yield and quality of sunflower can be obtained under water with the application of higher rates of potassium.

**Supporting information**

S1 Dataset. (XLSX)

**Author Contributions**

**Conceptualization:** Javed Shabbir Dar, Mumtaz Akhtar Cheema, Muhammad Ishaq Asif Rehmani, Muhammad Amjad Bashir, Suliman M. Alghanem, Fahad Mohammed Al-Zuaibr, Mohammad Javed Ansari, Kamel Hessini.

**Data curation:** Javed Shabbir Dar, Muhammad Ishaq Asif Rehmani.

**Formal analysis:** Javed Shabbir Dar, Muhammad Ishaq Asif Rehmani, Shahjahan Rajput.
**Funding acquisition:** Kamel Hessini.

**Investigation:** Shahnwaz Khuhro.

**Methodology:** Muhammad Ishaq Asif Rehmani, Ahmad Latif Virk.

**Project administration:** Muhammad Amjad Bashir.

**Resources:** Mumtaz Akhtar Cheema.

**Software:** Sajid Hussain, Suliman M. Alghanem.

**Supervision:** Mumtaz Akhtar Cheema.

**Validation:** Shahjahan Rajput.

**Visualization:** Shahjahan Rajput, Ahmad Latif Virk, Muhammad Amjad Bashir.

**Writing – original draft:** Javed Shabbir Dar.

**Writing – review & editing:** Javed Shabbir Dar, Mumtaz Akhtar Cheema, Shahnwaz Khuhro, Sajid Hussain, Muhammad Amjad Bashir, Suliman M. Alghanem, Fahad Mohammed Al-Zuaibr, Mohammad Javed Ansari, Kamel Hessini.

**References**

1. Davis KF, Rulli MC, Seveso A, D’Odorico P (2017) Increased food production and reduced water use through optimized crop distribution. Nature Geoscience 10: 919–924.

2. Mueller ND, Gerber JS, Johnston M, Ray DK, Ramankutty N, et al. (2012) Closing yield gaps through nutrient and water management. Nature 490: 254–257. https://doi.org/10.1038/nature11420 PMID: 22932270

3. Virk AL, Farooq MS, Ahmad A, Khaliq T, Rehmani MIA, et al. (2021) Effect of seeding age on growth and yield of fine rice cultivars under alternate wetting and drying system. Journal of Plant Nutrition 44: 1–15.

4. Farid M, Ali S, Rizwan M, Ali Q, Saeed R, et al. (2018) Phyto-management of chromium contaminated soils through sunflower under exogenously applied 5-aminolevulinic acid. Ecotoxicology and Environmental Safety 151: 255–265. https://doi.org/10.1016/j.ecoenv.2018.01.017 PMID: 29353175

5. Ilyas M, Nisar M, Khan N, Hazrat A, Khan AH, et al. (2020) Drought Tolerance Strategies in Plants: A Mechanistic Approach. Journal of Plant Growth Regulation; 40(3), 926–944.

6. D’Odorico P, Davis KF, Rosa L, Carr JA, Chiarelli D, et al. (2018) The Global Food-Energy-Water Nexus. Reviews of Geophysics 56: 456–531.

7. Askari-Khorasgani O, Rehmani MIA, Wani SH, Kumar A (2021) Osmotic Stress: An Outcome of Drought and Salinity. Handbook of Plant and Crop Physiology: CRC Press. pp. 445–464.

8. Raza MAS, Saleem MF, Khan IH, Hussain MB, Shah GM (2018) Amelioration in Growth and Physiological Efficiency of Sunflower (Helianthus annuus L.) under Drought by Potassium Application. Communications in Soil Science and Plant Analysis 49: 2291–2300.

9. Yu H, Zhang Q, Sun P, Song C (2018) Impact of Droughts on Winter Wheat Yield in Different Growth Stages during 2001–2016 in Eastern China. International Journal of Disaster Risk Science 9: 376–391.

10. Hussain S, Saleem MF, Iqbal J, Ibrahim M, Atta S, et al. (2014) Exogenous application of abscisic acid may improve the growth and yield of sunflower hybrids under drought. Pakistan Journal of Agricultural Sciences 51: 49–58.

11. Ahmad A, Aslam Z, Iqbal N, Idrees M, Bellitürk K, et al. (2019) Effect of exogenous application of osmo-lytes on growth and yield of wheat under drought conditions. Journal of Environmental and Agricultural Sciences 21: 6–13.

12. Hussain M, Farooq S, Hasan W, Ul-Allah S, Tanveer M, et al. (2018) Drought stress in sunflower: Physiological effects and its management through breeding and agronomic alternatives. Agricultural Water Management 201: 152–166.

13. Bodner G, Nakhqforoosh A, Kaul H-P (2015) Management of crop water under drought: a review. Agronomy for Sustainable Development 35: 401–442.

14. Chai Q, Gan Y, Zhao C, Xu H-L, Waskom RM, et al. (2016) Regulated deficit irrigation for crop production under drought stress. A review. Agronomy for Sustainable Development 36: 3.
15. Zamani S, Naderi MR, Soleymani A, Nasiri BM (2020) Sunflower (Helianthus annuus L.) biochemical properties and seed components affected by potassium fertilization under drought conditions. Ecotoxicology and Environmental Safety 190: 110017. https://doi.org/10.1016/j.ecoenv.2019.110017 PMID: 31846862

16. Ata-Ul-Karim ST, Zhu Y, Cao Q, Rehmani MIA, Cao W, et al. (2017) In-season assessment of grain protein and amylose content in rice using critical nitrogen dilution curve. European Journal of Agronomy 90: 139–151.

17. Sarkar D, Baishya LK (2017) Nutrient Use Efficiency. In: Naeem M, Ansari AA, Gill SS, editors. Essential Plant Nutrients: Uptake, Use Efficiency, and Management. Cham: Springer International Publishing. pp. 119–146.

18. Nazir MF, Sarhaz Z, Mangi N, Nawaz Shah MK, Mahmood T, et al. (2021) Post-Anthesis Mobilization of Stem Assimilates in Wheat under Induced Stress. Sustainability 13: 5940.

19. Nasim W, Ahmad A, Amin A, Tariq M, Awais M, et al. (2018) Radiation efficiency and nitrogen fertilizer impacts on sunflower crop in contrasting environments of Punjab, Pakistan. Environmental Science and Pollution Research 25: 1822–1836. https://doi.org/10.1007/s11356-017-0592-z PMID: 29103112

20. Ata-Ul-Karim ST, Cao Q, Zhu Y, Tang L, Rehmani MIA, et al. (2016) Non-destructive Assessment of Plant Nitrogen Parameters Using Leaf Chlorophyll Measurements in Rice. Frontiers in Plant Science 7: 1829. https://doi.org/10.3389/fpls.2016.01829 PMID: 28018373

21. Nair KP (2019) Soil Fertility and Nutrient Management. Intelligent Soil Management for Sustainable Agriculture: The Nutrient Buffer Power Concept. Cham: Springer International Publishing. pp. 165–189.

22. Röös E, Mie A, Wrivstad M, Salomon E, Johansson B, et al. (2018) Risks and opportunities of increasing yields in organic farming. A review. Agronomy for Sustainable Development 38: 14.

23. Rehmani MIA, Wei G, Hussain N, Ding C, Li G, et al. (2014) Yield and quality responses of two indica rice hybrids to post-anthesis asymmetric day and night open-field warming in lower reaches of Yangtze River delta. Field Crops Research 156: 231–241.

24. Ahmad Z, Anjum S, Waraich EA, Ayub MA, Ahmad T, et al. (2018) Growth, physiology, and biochemical activities of plant responses with foliar potassium application under drought stress—a review. Journal of Plant Nutrition 41: 1734–1743.

25. Ramzan H, Tahir MA, Abbas G, Mehmoood T (2020) Potassium nutrient management in wheat through 4R nutrient stewardship. Journal of Environmental and Agricultural Sciences 22: 10–16.

26. Ahmad A Z, Aslam M Z, Ilyas, Ameer H., Mahmood A, et al. (2019) Drought stress mitigation by foliar feeding of potassium and amino acids in wheat. Journal of Environmental and Agricultural Sciences 18: 10–18.

27. Ali AB, Altayeb OA, Alhadi M, Shuang-En Y (2014) Effect of different levels nitrogen and phosphorus fertilization on yield and chemical composition hybrid sunflower grown under irrigated condition. Journal of Environmental and Agricultural Sciences 1: 7–14.

28. Zahoor R, Zhao W, Abid M, Dong H, Zhou Z (2017) Potassium application regulates nitrogen metabolism and osmotic adjustment in cotton (Gossypium hirsutum L.) functional leaf under drought stress. Journal of Plant Physiology 215: 30–38. https://doi.org/10.1016/j.jplph.2017.05.001 PMID: 28527336

29. Gujar A, Burio M, Kubar MS, Kubar KA, Kamran M, et al. (2018) Agronomic performance of sunflower Helianthus annuus L.) against different sources and levels of potassium fertilization. Journal of Environmental and Agricultural Sciences 15: 18–27.

30. Hameed K, Azeem K (2017) Pakistan need to be self sufficient in edible oil production. Journal of Energy Technologies and Policy 7: 48–57.

31. Tabasssum MI, Aslam M, Javed MI, Salim J, Sarwar M, et al. (2020) Hybrid development programme of sunflower in Pakistan: A review. J Agric Res 58: 145–156.

32. Dar JS, Cheema MA, Wahid MA, Saleem MF, Farooq M, et al. (2009) Role of planting pattern and irrigation management on growth and yield of spring planted sunflower (Helianthus annuus). International Journal of Agriculture and Biology Science 11: 701–706.

33. Hunt R (1978) Plant growth analysis. The institute Biology’s studies in Biology: Edward Arnold (Pub.) Ltd.

34. Nasim W, Belhouchette H, Tariq M, Fahad S, Hammad HM, et al. (2016) Correlation studies on nitrogen for sunflower crop across the agroclimatic variability. Environmental Science and Pollution Research 23: 3658–3670. https://doi.org/10.1007/s11356-015-5613-1 PMID: 26498803

35. A.O.A.C. (1990) Official method of analysis. Association of official analytical chemists: Arlington, Virginia, U.S.A.

36. Freed R, Scott D (1986) MSTAT-C. Crop and Soil Science Department, Michigan State University, Michigan, USA.
37. Kumar P, Kumar T, Singh S, Tuteja N, Prasad R, et al. (2020) Potassium: A key modulator for cell homeostasis. Journal of Biotechnology 324: 198–210. https://doi.org/10.1016/j.jbiotec.2020.10.018 PMID: 33080306

38. de Bang TC, Husted S, Laursen KH, Persson DP, Schjoerring JK (2021) The molecular–physiological functions of mineral macronutrients and their consequences for deficiency symptoms in plants. New Phytologist 229: 2446–2469. https://doi.org/10.1111/nph.17074 PMID: 33175410

39. Sardans J, Puñuelas J (2021) Potassium Control of Plant Functions: Ecological and Agricultural Implications. Plants 10: 419. https://doi.org/10.3390/plants10020419 PMID: 33672415

40. Srivastava AK, Shankar A, Nalini Chandran AK, Sharma M, Jung K-H, et al. (2019) Emerging concepts of potassium homeostasis in plants. Journal of Experimental Botany 71: 608–619.

41. Cui J, Tcherkez G (2021) Potassium dependency of enzymes in plant primary metabolism. Plant Physiology and Biochemistry 166: 522–530.

42. Hasanuzzaman M, Bhuyan MHMB, Nahar K, Hossain MS, Mahmud JA, et al. (2018) Potassium: A Vital Regulator of Plant Responses and Tolerance to Abiotic Stresses. Agronomy 8: 31.

43. Tighe-Neira R, Alberdi M, Arce-Johnson P, Romeiro J, Reyes-Díaz M, et al. (2018) Role of Potassium in Governing Photosynthetic Processes and Plant Yield. In: Hasanuzzaman M, Fujita M, Ooku H, Nahar K, Hawrylak-Nowak B, editors. Plant Nutrients and Abiotic Stress Tolerance. Singapore: Springer Singapore. pp. 191–203.

44. Tittal M, Mir RA, Jatav KS, Agarwal RM (2021) Supplementation of potassium alleviates water stress-induced changes in Sorghum bicolor L. Physiologia Plantarum 172: 1149–1161. https://doi.org/10.1111/ppl.13306 PMID: 33314117

45. Liu P-C, Peacock WJ, Wang L, Furbank R, Larkum A, et al. (2020) Leaf growth in early development is key to biomass heterosis in Arabidopsis. Journal of Experimental Botany 71: 2439–2450. https://doi.org/10.1093/jxb/eraa006 PMID: 31960925

46. Basu S, Ramegowda V, Kumar A, Pereira A (2016) Plant adaptation to drought stress. F1000Research 5: F1000 Faculty Rev-1554. https://doi.org/10.12688/f1000research.7678.1 PMID: 27441087

47. Botyanszka L, Zivcak M, Chovancek E, Sytar O, Barek V, et al. (2020) Chlorophyll Fluorescence Kinetics May Be Useful to Identify Early Drought and Irrigation Effects on Photosynthetic Apparatus in Field-Grown Wheat. Agronomy 10: 1275.

48. Ahmadihak A, Marufinia A (2016) Effect of reduced plant height on drought tolerance in rice. 3 Biotech 6: 221. https://doi.org/10.1007/s13205-016-0542-3 PMID: 28330293

49. Rauf S (2008) Breeding sunflower (Helianthus annuus L.) for drought tolerance. Communications in Biometry and Crop Science 3: 29–44.

50. Hossain M, Khatun A, Talukder M, Dewan M, Uddin M (2010) Effect of drought on physiology and yield contributing characters of sunflower. Bangladesh Journal of Agricultural Research 35: 113–124.

51. Shah MN, Shafl MJ, Wahid A (2019) Influence of foliage applied moringa leaf extract on growth and yield of sunflower (Helianthus annuus L.) underwater deficit conditions. Journal of Arable Crops and Marketing 1: 45–52.

52. Lake L, Sadras VO (2021) Lentil yield and crop growth rate are coupled under stress but uncoupled under favourable conditions. European Journal of Agronomy 126: 126266.

53. Mannan MA, Mia S, Halder E, Dijkstra FA (2021) Biochar application rate does not improve plant water availability in soybean under drought stress. Agricultural Water Management 253: 106940.

54. Santonoceto C, Hocking PJ, Braschkat J, Randall PJ (2002) Mineral nutrient uptake and removal by canola, Indian mustard, and Linola in two contrasting environments, and implications for carbon cycle effects on soil acidification. Australian Journal of Agricultural Research 53: 459–470.

55. Schlegel AJ, Assefa Y, O'Brien D, Lamm FR, Haag LA, et al. (2016) Comparison of Corn, Grain Sorghum, Soybean, and Sunflower under Limited Irrigation. Agriculture Journal 108: 670–679.

56. Aiken R, Lamm F. Irrigation of oilseed crops; 2006. Colorado State University. Libraries.

57. Černý I, Veveřková A, Kovář M, Pačuta V, Molnárová J (2014) Influence of temperature and moisture conditions of locality on the yield formation of sunflower (Helianthus annuus L.). Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 59: 99–104.

58. Flagella Z, Rotunno T, Tarantino E, Di Caterina R, De Caro A (2002) Changes in seed yield and oil fatty acid composition of high oleic sunflower (Helianthus annuus L.) hybrids in relation to the sowing date and the water regime. European Journal of Agronomy 17: 221–230.

59. Angeloni P, Aguirrezábal L, Echarte MM (2021) Assessing the mechanisms underlying sunflower grain weight and oil content responses to temperature during grain filling. Field Crops Research 262: 108040.
60. Luan X, Vico G (2021) Canopy temperature and heat stress are increased by compound high air temperature and water stress and reduced by irrigation—a modeling analysis. Hydrol Earth Syst Sci 25: 1411–1423.

61. Fageria NK, Oliveira JP (2014) Nitrogen, Phosphorus and Potassium Interactions in Upland Rice. Journal of Plant Nutrition 37: 1586–1600.

62. Duncan EG, O’Sullivan CA, Roper MM, Palta J, Whisson K, et al. (2018) Yield and nitrogen use efficiency of wheat increased with root length and biomass due to nitrogen, phosphorus, and potassium interactions. Journal of Plant Nutrition and Soil Science 181: 364–373.