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Optimizing water-stressed mungbean for climate-smart sustainable intensification: Potassium's role in improving soil moisture, physio-biochemical traits, and yield sustainability

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Abstract

Agronomic management offers a practical approach for cultivating mungbean (*Vigna radiata* L. Wilczek) under water-stressed dry conditions. This study investigated the effects of water stress (WS) on mungbean yield productivity, plant water relations, and physicochemical changes in response to different potassium (K) application rates. Two genotypes—drought-resistant BMX-08010-2 (G1) and sensitive cultivar BARI Mung-1 (G2)—were employed alongside seven levels of potassium fertilization treatments, namely, well-watered + recommended K fertilization (RKF) in the form of muriate of potash (KL_1), WS + RKF (KL_2), WS + 25% additional K with RKF (KL_3), WS + 50% additional K with RKF (KL_4), WS + 75% additional K with RKF

Abbreviations: BARI, Bangladesh Agricultural Research Institute; BY, biological yield; CTD, canopy temperature depression; DAS, days after sowing; DW, dry weight; GY, grain yield; HI, harvest index; MC, moisture content; MSI, membrane stability index; PWP, permanent wilting point; RKF, recommended K fertilization; ROS, reactive oxygen species; RWC, relative water content; SS, soluble sugar; SWD, soil water depletion; WS, water stress; WUE, water use efficiency; WW, well-watered; XER, xylem exudation rate.

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(KL_5), WS + 100% additional K with RKF (KL_6), and WS + 125% additional K with RKF (KL_7). All treatments were conducted under a rain-out shelter using a split-plot design with three replications. The results revealed that various physicochemical and agronomic traits were affected under WS, including water use efficiency (WUE), chlorophyll content, relative water content, xylem exudation rate, membrane stability index, proline, and soluble conditions, particularly temperature depression, biological yield, harvest index, and seed yield productivity. However, the application of additional K (KL_3–KL_7) improved the performance of all these traits under WS conditions, with the most notable improvement observed at the highest application level (KL_7). Specifically, the KL_7 treatment increased WUE to 8.14 kg ha^{-1} mm^{-1} and grain yield to 1093 kg ha^{-1}, whereas the KL_2 treatment, without additional K, recorded the lowest WUE (4.73 kg ha^{-1} mm^{-1}) and grain yield of 825 kg ha^{-1}. Compared to lower K applications under WS, the KL_7 treatment resulted in a 32.52% increase in grain production, with overall yields ranging from 1410 kg ha^{-1} using 281 mm water (KL_1) to 825 kg ha^{-1} using 175 mm water (KL_2). These findings support the role of K supplementation in mitigating the adverse effects of WS and offer a promising strategy for using this approach as a model for enhancing WUE and crop resilience in achieving sustainable water development under climate-smart agricultural practices.

Plain Language Summary

Water stress (WS) reduces plant water supplies, reducing yield worldwide, especially in Bangladesh. Mungbean cultivation is susceptible to dry weather. Potassium (K) helps plants use water efficiently and maintain physiological balance during drought season. This study aimed to examine the effect of applying 0%–125% K fertilizer on mungbean plants' WS response. A controlled WS study assessed the impact of K on the development, yield, and internal biological alterations of two mungbean plant varieties: one that could or could not manage drought. The study revealed significant production and growth losses in mungbean plants under WS. Supplemental K fertilizer boosted plant growth. Adding 125% K yielded the largest benefits. Compared to WS treatments with lower potassium levels, grain yield rose by 32.52%. Adding K to mungbean crops enhances drought and WS tolerance, boosting health and yield production. This approach promotes climate-smart farming in drought-prone areas.

1 | INTRODUCTION

Approximately 47% of the country's landmass—home to about 53% of the population in Bangladesh—is affected by water stress (WS) due to severe drought (Sarkar et al., 2024). In addition to crops used for agriculture, drought also adversely impacts forests, orchards, and the broader environmental ecosystem. As a result, drought is recognized as a significant challenge to achieving sustainable agricultural development and ensuring food security in the country (Alamgir et al., 2015). Furthermore, global food security for future generations is under serious threat due to the frequent occurrence of WS (M. R. Islam et al., 2022), which affects 40%–60% of the world's agricultural lands (Azadi et al., 2018). Each year, around 2.7 million ha of land face the threat of drought and WS in agriculture, with an estimated 41%–50% of the country expected to encounter drought conditions at various times (ICDDR and USAID, 2024; Tanner et al., 2007). Specifically, the phenomenon of drought has affected 12.49 million ha of cultivable land throughout the "Aman" rice season and 9.32 million ha of agricultural land during the Rabi (winter) season.

Mungbean (*Vigna radiata* L. Wilczek), considered as a summer and winter crop, is an important legume crop in South Asia, playing a significant role in ensuring food and nutritional security for the region's growing population (Iqbal et al., 2023). It is the second most important pulse crop grown in Bangladesh, contributing to 32% of the country's total pulse production (AIS, 2022). The majority of farmers grow mungbean as a short-duration catch crop on different types of soil under rainfed conditions. During the mungbean growing period, temperature often increases to 40°C–42°C with a long duration of WS. These adverse conditions negatively affect the growth, development, and yield of summer mungbean (R. R. Kumar et al., 2011; Sabagh et al., 2020). Developing plant resilience to WS has become a critical challenge that necessitates the development of stress-tolerant crops or varieties alongside effective agronomic management practices. However, achieving tolerance to WS at the cellular level is particularly challenging due to the complex interactions between stress factors and the molecular, biochemical, and physiological processes that regulate plant growth and development (Oguz et al., 2022; Seleiman et al., 2021).

WS significantly affects a wide range of physiological and biochemical processes that are essential to crop development and yield (Mahajan et al., 2023; Singh et al., 2021). The extent of these changes depends on the intensity and duration of WS, as well as the genetic resilience of cultivars of mungbean (Chaves et al., 2002). The production of excess reactive oxygen species (ROS) and proline is part of the aforementioned functions (Alsamadany, 2022), which hinders the roots' ability to absorb water and nutrients (Bangar et al., 2019; Singh et al., 2021). WS also affects stomatal closure and opening (Agurla et al., 2018), inhibits chlorophyll (Chl) synthesis, and disrupts light-harvesting pigment-protein complexes and photosystem II (Batra et al., 2014; M. R. Islam et al., 2022). Not only that, it damages membranes, which reduces photosynthetic efficiency (Farooq et al., 2009; Maduraimuthu et al., 2023; Ramadan et al., 2023).

Potassium (K) is the third macronutrient obligatory for plant growth, physiological processes, and sustainable crop production (Mostofa et al., 2022). The yield reduction of pulse crops caused by WS can be mitigated through the application of additional K or by more efficient use of K (Ashraf et al., 2024; Sangakkara et al., 2000). Under WS, adequate supplementation of K improves plant water relations and photosynthetic rates, thereby increasing crop productivity (Sangakkara et al., 2000). It also maintains cell turgor pressure, which is crucial for sustaining growth. Moreover, K plays an important role in osmotic regulation within plant cells and facilitates water uptake along the soil-plant gradient (Kumari et al., 2022). It reduces soil moisture loss by lowering the transpiration rate, achieved through regulating stomatal opening and closing, thereby improving WS tolerance (Brag, 1972; Umar & Moinuddin, 2002). It plays a key role in activating more than 60 enzymes (P. Kumar et al., 2020), enhances protein content in pulse grains (Srinivasarao et al., 2003), acts as an anti-stress element, and promotes plant survival against stress through nutritional and physiological mechanisms (Mostofa et al., 2022). It also assists in maintaining cation-anion balance in plants, accounting for 3%–5% of the plant's dry weight (DW) (Sardans & Peñuelas, 2021). Additionally, K stimulates root growth, improving nutrient absorption and water retention (Sustr et al., 2019; Xu et al., 2021). It regulates several biochemical processes under adverse conditions (Hasanuzzaman et al., 2018; Imtiaz et al., 2022), which helps maintain high pH levels in the chloroplast stroma, and protects against photo-oxidative damage (Hasanuzzaman et al., 2018). Furthermore, K application has been shown to enhance mungbean yield (Eroğlu & Önder, 2023).

Conversely, WS often leads to the overproduction of ROS, causing lipid peroxidation, protein oxidation, enzyme inhibition, and activation of the programmed cell death pathway, ultimately resulting in cell death (Sharma et al., 2012). However, sustainable yields can be achieved through effective K management, which plays a vital role in enhancing plant tolerance to stress conditions (Johnson et al., 2022). A variety of research investigations have shown that K fertilization mitigates the negative impacts of WS on the development and productivity of several pulse crops, such as mungbean (Ali et al., 2023; Fooladivanda et al., 2014; M. R. Islam et al., 2024), soybean (Steiner et al., 2022), faba beans (Abdel Wahab & Abd-Alla, 1995), and black gram (Shahi et al., 2019).

Core Ideas

- Targeted nutrient management alleviates climate-driven drought and water stress in mungbeans.
- 125% K supplementation increases soil moisture, enhances physiological resilience, improves biochemical balance, and raises seed yield by 32.52%.
- Key benefits of extra K application include enhanced water use efficiency (up to 8.14 kg ha^{-1} mm^{-1}), chlorophyll content, relative water content, membrane stability, xylem exudation, and canopy temperature depression.
- Applying additional K reduces stress markers such as proline and soluble sugars, indicating improved osmotic regulation and membrane health.
- The drought-tolerant genotype (G1) consistently outperformed the drought-sensitive genotype (G2) in all traits under stress.

Sustainable agronomic practices that conserve vital resources such as water and fertilizers are essential for implementing climate-smart agriculture (CSA) and pursuing sustainable intensification (SI) to produce more and better food security with fewer resources. These practices help mitigate soil fertility loss and address the challenges of climate change. In this context, the CSA and SI approaches focus on increasing food production from existing farmland by optimizing and conserving these resources, while minimizing negative environmental impacts (Rahman et al., 2021, 2024). Given the environmental concerns associated with climate-smart sustainable intensification, particularly for summer mungbean cultivation in Bangladesh, strategic potassium (K) management can emerge as an effective approach to mitigate the adverse effects of WS on mungbean growth and yield. Moreover, applying targeted K levels during final land preparation can enhance crop performance by improving water use efficiency (WUE), Chl content, relative water content (RWC), xylem exudation rate (XER), membrane stability index (MSI), proline and soluble sugar (SS) content, canopy temperature depression (CTD), and so forth. Additionally, combining drought-tolerant genotypes with optimized potassium application can synergistically reduce negative impacts of WS, thereby enhancing yield sustainability. In light of these considerations, the present study was undertaken to evaluate the effect of supplementary K fertilization in mitigating the detrimental impacts of WS on plant water relations, physicochemical alterations, and the yield productivity of summer mungbean.

2 | MATERIALS AND METHODS

2.1 | Location and test materials

The present study was conducted in a rainout shelter at the Regional Agricultural Research Station in Ishwardi, Pabna, Bangladesh, over two consecutive years (2018 and 2019). The study site, as shown in Figure 1, is 16 meters above sea level, located at 24.03˚ N latitude and 89.05˚ E longitude. This soil type, common in Bangladesh, is classified as "High Ganges River Floodplain Soil" (Agro-ecological Zone-11) and belongs to the Ishwardi soil series. It is characterized as calcareous dark gray floodplain soil. Two mungbean genotypes were used: BMX-08010-2 (G1), known for its tolerance to WS, and BARI Mung-1 (G2), recognized as sensitive to WS. These genotypes were identified through laboratory screening that evaluated germination, seedling growth, and relative performance under water deficit stress induced by polyethylene glycol. BARI Mung-1 is a popular variety in Bangladesh, while BMX-08010-2 is a high-yielding advanced line developed through hybridization at the Pulses Research

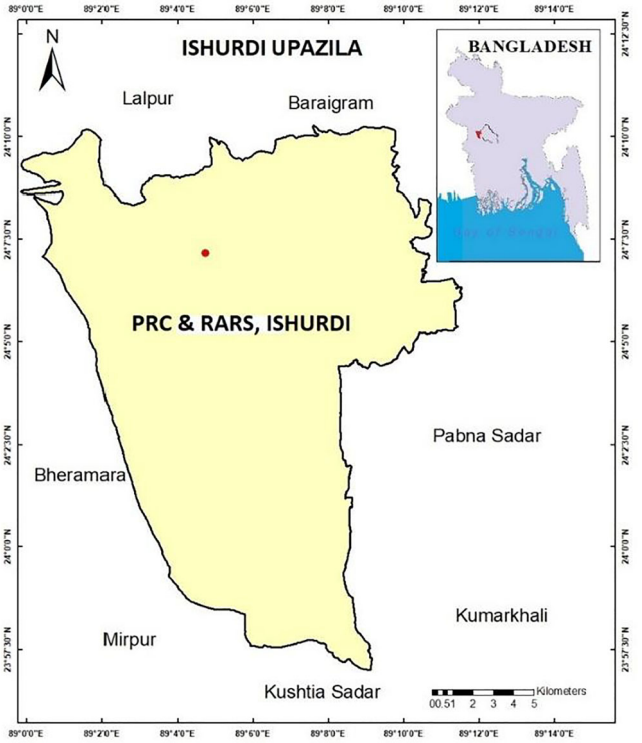


FIGURE 1 Aerial map and location of the experimental site and observation well (red dot) at RARS (Regional Agricultural Research Station), Ishwardi, Pabna in Bangladesh.

Centre, Bangladesh Agricultural Research Institute, located in Ishwardi, Pabna, Bangladesh.

2.2 | Soil and weather

Prior to sowing mungbean, the physical and chemical characteristics of the soil were analyzed at a depth of 0–15 cm within the soil profile. The soil was classified as a clay loam in structure and exhibited a slightly alkaline nature. The field capacity of the soil was recorded at 29.20%, with a bulk density of 1.40 g/cc and a permanent wilting point (PWP) of 13%. Additional details on the soil characteristics at the experimental site are provided in Table 1. Climatic data pertaining to the crop growth period were obtained from the meteorological facility of the Bangladesh Sugarcrop Research Institute in Pabna, located approximately 400 m from the experimental field, are presented in Table 2.

2.3 | Experimental design and treatments

The research was conducted using a split-plot design with three replications. Mungbean genotypes were assigned to the main plots, while the seven potassium (K) fertilization treatments were randomly assigned to the subplots. For the main

TABLE 1 The experimental site's initial physical and chemical properties.

Items	Soil texture (clay loamy)			pH	Organic matter (%)	N (%)	P (μg ml^{-1})	K (meq 100 g^{-1} soil)	S (μg ml^{-1})	B (μg ml^{-1})	Zn (μg ml^{-1})
Analytical value (avg.)	Sand (18.1%)	Silt (31.9%)	Clay (48.6%)	7.3	1.23	0.06	34.01	0.25	42.43	0.29	3.21
Critical level	–	–	–	–	–	0.12	10.00	0.12	10.00	0.20	0.60

TABLE 2 Weather data (decades-wise) during the crop-growing period.

Month	Decades	Air temperature		Mean relative humidity (%)	Rainfall (mm)	Sunshine hour (day^{-1})
		Max. (°C)	Min. (°C)			
March	1	30.8	17.4	69.8	0.0	9.1
	2	33.9	17.9	71.0	0.0	8.3
	3	33.8	21.3	78.7	54.5	6.4
April	1	32.6	20.7	81.0	46.0	8.2
	2	33.9	22.3	82.5	124.5	8.0
	3	34.5	23.0	81.8	77.8	5.8
May	1	32.7	23.9	84.3	69.1	4.9
	2	31.8	22.6	82.8	67.8	5.1
	3	34.1	25.4	84.5	45.9	5.3

plot treatments (Factor A), two mungbean genotypes were utilized: BMX-08010-2 (WS tolerant: G1) and BARI Mung-1 (WS susceptible: G2). The seven K fertilization treatments that were utilized as subplot treatments (Factor B) were as follows: (1) Well-watered (WW) + recommended K fertilization (RKF, i.e., 18 kg K ha^{-1}) (KL_1), (2) WS + RKF (KL_2), (3) WS + 25% additional K with RKF (KL_3), (4) WS + 50% additional K with RKF (KL_4), (5) WS + 75% additional K with RKF (KL_5), (6) WS + 100% additional K with RKF (KL_6), and (7) WS + 125% additional K with RKF (KL_7). The inclusion of a 125% K treatment (KL7) is justified by evidence indicating that elevated K levels (125 kg ha^{-1}) enhance WS tolerance and productivity in legumes, particularly mungbean (M. R. Islam et al., 2024; Hussain et al., 2016; Zörb et al., 2014). Previous studies also highlight the physiological necessity of higher K in stress-prone environments (Ashraf et al., 2024). The subplot treatments were arranged randomly in 3 m × 3 m plots. The RKF used was determined by Azad et al. (2017).

2.4 | Fertilization

Potassium fertilizer was applied according to the prescribed treatments in the form of muriate of potash. A maintenance dose of other fertilizers was also applied at a rate of 20-17-10-2 kg of N-P-S-B ha^{-1} (nitrogen-phosphorus-sulfur-boron) (Azad et al., 2017) using urea, triple super phosphate, gypsum, and boric acid, respectively. All fertilizers have been thoroughly and precisely blended with the soil during the firm land preparation.

2.5 | Sowing and farming techniques

Note that 8 h prior to sowing, the mungbean seeds were treated with Provax-200 WP at a dosage of 3.5 g kg^{-1} of seed. Afterward, seeds were sown at a rate of 25 kg ha^{-1} using the continuous sowing method, with rows spaced 30 cm apart. Following a period of 15 days after emergence, mungbean specimens were subjected to thinning, maintaining an interplant spacing of approximately 6–7 cm. Weed control was conducted manually at 15 and 30 days after sowing (DAS). Applying a 0.5 mL dilution of Imidacloprid (Imitaf 20 SL) per liter of water at 35 DAS (100% flowering stage) and 42 DAS (peak flowering and 100% podding stage) protected the crop against flower thrips. Similarly, the pod borer infestation was managed by applying 1 mL of Lambda-Cyhalothrin (Karate 2.5 EC/Reeva 2.5 EC) to a liter of water three to four times weekly after podding was complete (M. R. Islam et al., 2021, 2022).

2.6 | Maintenance of soil moisture levels

To ensure sufficient germination and seedling establishment, all plots received a post-sowing irrigation of 53 mm based on the prevailing soil moisture conditions. Due to the fact that it was watered at three crucial periods of development—the initial trifoliate leaf stage (20 DAS), the flowering stage (35 DAS), and the pod-filling stage (45 DAS)—the KL_1 treatment got an adequate amount of water throughout the whole of the growth period. Subsequently, only the WW treatments

received three scheduled irrigations at 20, 35, and 45 DAS (M. R. Islam et al., 2021), with irrigation volumes determined by measuring soil moisture content (MC) and calculating the deficit to reach field capacity. By measuring the soil moisture levels at each irrigation schedule, the total depth (or volume) of water (d) required for the WW treatment was estimated for a 45-cm functional root zone depth, as per Michael (1996), where the effective root zone depth accounts for 50% of the total moisture as follows:

$$\textit{Depth (or volume)} \text{ of water (d)} = \frac{\text{Field capacity (\%)} - \text{Moisture content at the time of irrigation (\%)}}{100} \times \text{bulk density (g/cc)} \times \text{root zone depth (cm)}$$

For WS treatments, no irrigation was applied beyond the initial 53 mm. A rainout shelter was used to exclude rainfall and maintain drought conditions throughout the entire growth period.

2.7 | Data measurement

2.7.1 | Soil moisture levels

The soil MC of each treatment plot was measured gravimetrically using a hand-driven auger in order to track water balance and evaluate the effects of predicted groundwater. For this purpose, soil samples were collected from the center of each plot at different soil profile depths (0–15 cm, 15–30 cm, and 30–45 cm) at 10-day intervals from sowing to crop maturity. Before and after each treatment, soil moisture depletion (SMD) was confirmed using soil moisture sampling. Each sampling date was followed by the collection of duplicate soil samples, which were promptly sealed in aluminum cans and sent to the lab. The samples were weighed first, oven-dried at 105°C for 72 h, and weighed again. Finally, the soil MC was calculated on a DW basis as follows:

$$\%\ \text{Soil moisture} = \frac{\text{Weight of moist soil} - \text{weight of oven dry soil}}{\text{Weight of oven} - \text{dry soil}} \times 100$$

In light of soil moisture observations confirming emergence, the experimental plot received a gentle watering (53 mm) to maintain the primary soil moisture at 28.13% (Table 1).

2.7.2 | Loss of soil water

The equation below was employed to calculate the quantity of soil water depleted within the effective root zone (Eisenhauer et al., 2021):

$$\text{SWD} = \sum_{i=1}^{n} \frac{(\text{Mbi} - \text{Mei})}{100} \times \text{BDi} \times \text{Di}$$

where SWD is the soil water depletion (mm), Mbi is the moisture content of a certain soil layer at the beginning of the season, Mei is the moisture content in a certain layer of soil at the end of a season, n is the sum of all soil layers in the root zone (3), BDi is the soil layer-specific bulk density, and Di is the measurement of the depth of the soil layer containing the root zone (mm).

2.7.3 | Water use efficiency

The performance of the yield and the water management practices was evaluated using WUE. The estimation of crop water uptake was carried out using the equation below (Molden, 1997):

$$\text{Water use efficiency (WUE)} = \frac{\text{Yield } \left(\text{kg ha}^{-1}\right)}{\text{Total water use (mm)}}$$

2.7.4 | Relative water content

Using the technique outlined by Barrs and Weatherley (1962), the fresh, turgid, and DWs of the highest uppermost trifoliate leaves that had completely expanded were used to determine RWC for each treatment. The turgid weight was determined by soaking the leaves in distilled water and letting them sit in a dark room at room temperature for 8 h. Afterward, excess water was gently blotted from the leaf surface using a paper towel, and the leaves were weighed. Afterward, the leaves were then dried in an oven at 80°C for 72 h to get their DW. The formula used for calculating RWC is provided below:

$$\text{Relative water content (RWC)} = \frac{\text{Fresh weight} - \text{dry weight}}{\text{Turgid weight} - \text{dry weight}} \times 100$$

2.7.5 | Xylem exudation rate

To measure the XER, the stem was first cut with a sharp knife in a slanting way at 5 cm above the base of the plant. Next, the clean and dry cotton that had been weighed earlier was positioned on the cut surface to gather the exudation sap for a duration of 1 h at room temperature. Subsequently, the cotton was encased in a polythene bag to safeguard against evaporation. Finally, the cotton's weight after adding the exudates was measured. The formula used is given below:

$$\text{Exudation rate} = \frac{(\text{Weight of cotton} + \text{sap}) - (\text{Weight of cotton})}{\text{Time } (h)}$$

2.7.6 | Proline content

The acid ninhydrin technique was used to evaluate the proline content from 0.5 g of fresh leaves from the uppermost third trifoliate (Bates et al., 1973). Using a UV-visible spectrophotometer (T60 UV) set at 520 nm wavelength, the optical densities of the sample and standard solutions were determined. Then, the concentration of proline was determined using a standard curve and shown as milligrams of proline per gram of fresh weight (FW).

2.7.7 | Chl content

The Chl content was extracted by soaking 0.1 g of fresh third trifoliate leaves in 10 mL of acetone that was 80% concentration and shaking the mixture with an electric horizontal shaker for a whole 24 h. By measuring the absorbance of the supernatant using a UV-visible spectrophotometer at wavelengths of 663 and 645 nm, the levels of chlorophyll a (Chl-a), chlorophyll b (Chl-b), and total chlorophyll (TChl) content were quantified (Witham et al., 1986).

2.7.8 | SS content

The SS content of mungbean was estimated by collecting dry third trifoliate leaf samples throughout the flowering and pod formation stages (Yoshida et al., 1976). Megagrams per gram of DW of SSs were determined using a standard curve.

2.7.9 | Membrane stability index

The procedure began with 100 mg of fresh leaf samples being added to two sets of test tubes, one with 10 mL of double-distilled water and the other with 20 mL. After subjecting one set to a 30-min water bath heated to 40°C, its electrical conductivity (EC1) was measured using an electrical conductivity meter. According to Sairam (1994), the electrical conductivity (EC2) of the second set was measured after 10 min of heating in a water bath boiling at 100°C (Sairam, 1994). This formula can be used to determine the MSI as follows:

$$\text{Membrane stability index (MSI)} = \left(1 - \frac{\text{EC1}}{\text{EC2}}\right) \times 100$$

2.7.10 | Canopy temperature depression

The CTD refers to the deviation between ambient air temperature and canopy temperature and is recognized as a key characteristic for measuring genotypes' response to low water utilization (Balota et al., 2007). Canopy temperatures (CT) were measured at a distance of 0.5–1 m from the edge of the plot and approximately 50 cm above the canopy, using an infrared thermometer (Model LT-300, Sixth Sense) positioned at a 30° angle from the horizon. Measurements were recorded at 35 and 45 DAS during the noon period under bright sunlight and minimal wind conditions, and at the same time air temperature was recorded simultaneously. The data represent the mean of three sets of measurements taken between 12:00 a.m. and 4:00 p.m. (Reynolds et al., 1994).

2.8 | Statistical analysis

A similar trend was found for the studied traits across the two successive years. Consequently, a pooled analysis was done using the recorded values of the respective traits. All response variables under study were subjected to statistical analysis using a two-way analysis of variance performed with the R-stat software program, following the procedures outlined by R Core Team (2020). The significance of treatment effects was assessed using the least significant difference test.

3 | RESULTS

3.1 | Soil MCs in different treatments

The MC in each treatment varied in response to the application of additional potassium (K) fertilizer (Figure 2). In the KL_1 treatment, where soil moisture was consistently

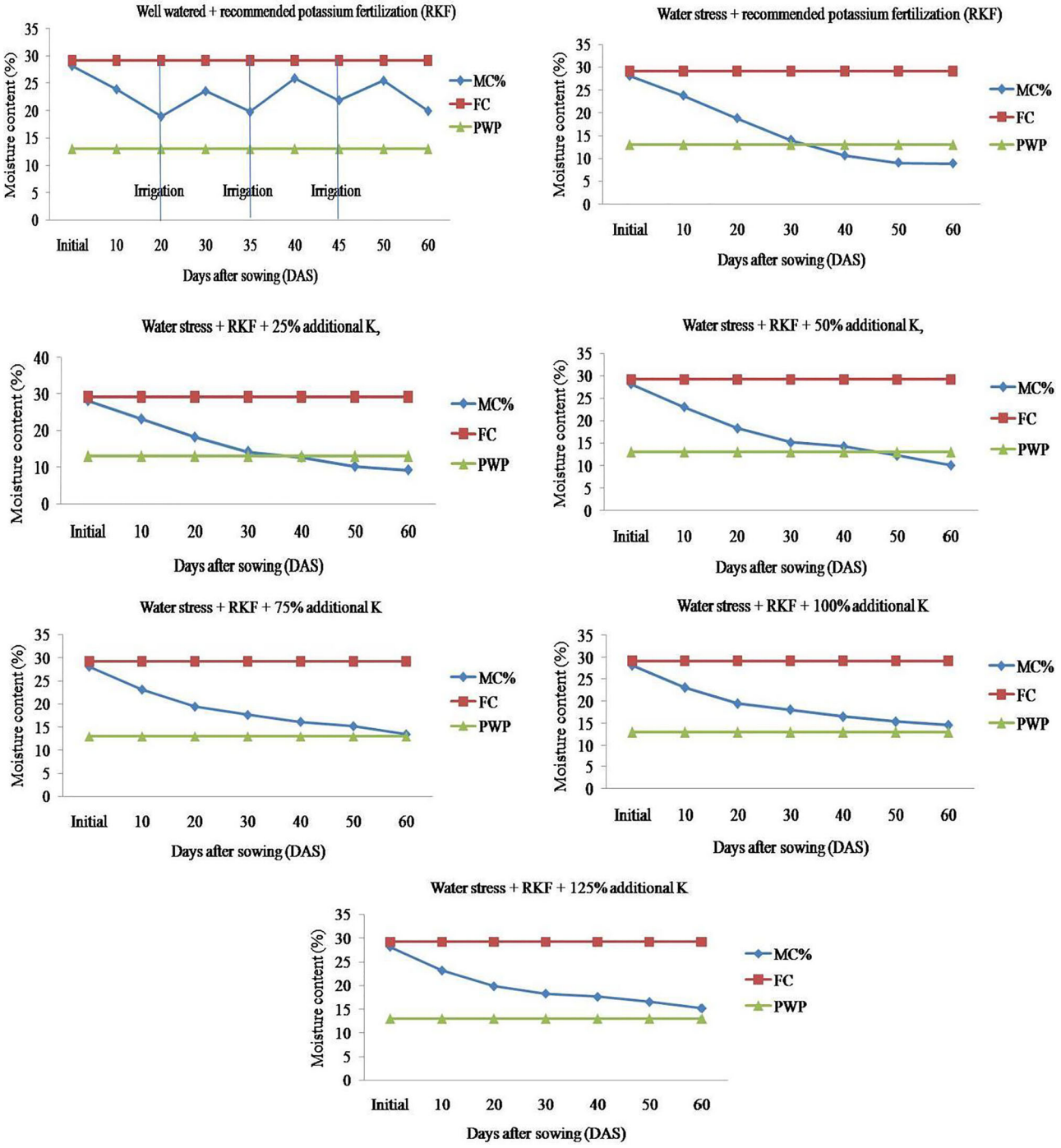


FIGURE 2 Variation of soil moisture content in well-watered (WW) and water stress (WS) with additional K fertilizer levels for different treatments, where FC, field capacity; MC, moisture content; PWP, permanent wilting point; RKF, recommended potassium fertilization; KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K, KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K, KL_7 = WS + RKF + 125% additional K.

maintained, plants exhibited optimal growth and development, resulting in the highest average grain yield (GY) of 1410 kg ha^{-1}. Additionally, this treatment extended the lifespan of mungbean plants compared to the WS treatments. On the other hand, the soil moisture levels of plants treated with KL_2 fluctuated between 10.63% and 8.87% after 35 DAS, whereas plants subjected to other treatments exhibited PWP soil moisture levels between 30 and 35 DAS. These conditions caused significant WS during the pre-flowering stage and later growth periods, forcing the plants to mature prematurely and resulting in a low GY (825 kg ha^{-1}). Applying 25% additional K fertilizer in the KL_3 treatment improved soil moisture levels compared to KL_2. Soil moisture remained above the PWP threshold between 35 and 40 DAS, with extreme water

TABLE 3 Water use efficiency (WUE) of mungbean under water stress (WS) conditions as influenced by supplementary K fertilization with recommended K fertilization (RKF).

Treatments	No. of irrigation	Post-sowing irrigation (mm)	Irrigation applied (mm)	Effective rainfall (mm)	Soil water depletion (mm)	Total water use (mm)	Water use efficiency (kg ha^{-1} mm^{-1})
KL_1	3	53	177	0[a]	51f	281a	5.01ef
KL_2	0	53	0	0	121a	175b	4.73f
KL_3	0	53	0	0	119a	173b	5.48de
KL_4	0	53	0	0	113b	167c	5.93d
KL_5	0	53	0	0	93c	146d	6.86c
KL_6	0	53	0	0	86d	139e	7.59b
KL_7	0	53	0	0	81e	134e	8.14a
LSD (5%)					3.68	5.82	0.47
CV (%)					2.18	1.88	4.24
LS					***	***	***

Note: The lowercase letters indicate the results of mean separation using the least significant difference (LSD) test at $p \leq 0.05$. Means followed by the same letter within a column are not significantly different, while those with different letters differ significantly. KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K.

Abbreviation: LS, level of significance.

[a]The crop was protected from rainout shelter.

***significant at $p = 0.001$.

deficits occurring after 40 DAS, ranging from 12.71% to 9.19%. While plants in the KL_3 treatment experienced WS during the flowering and later growth stages, the improved soil moisture levels positively influenced plant performance compared to the KL_2 treatment.

Plants subjected to the KL_4 treatment had access to sufficient moisture until 45 DAS, after which soil moisture levels dropped below the PWP, ranging from 12.27% to 10.12%. Consequently, plants under this treatment experienced WS from the pod-filling stage through the later growth period. In the KL_5 treatment, the soil moisture gradually decreased but remained above the PWP threshold throughout the growing period. These findings indicate that plants under this treatment maintained soil moisture within the available moisture range during the entire growing cycle. However, the available water amount was lower than the KL_1 treatment. Treatments KL_6 and KL_7 consistently maintained soil moisture levels above the wilting point (13%) throughout the growing period. As a result, plants experienced relatively less WS under these conditions, producing maximum GYs of 1057 and 1094 kg ha^{-1}, respectively, compared to treatments with lower K application levels.

3.2 | Physiological traits

The results indicate that SMD was substantially higher under the KL_2 treatment (121 mm) compared to KL_1, which recorded 51 mm (Table 3). Among the WS treatments, the KL_7 treatment, receiving 125% additional K over KL_2, exhibited the lowest SMD, outperforming treatments with lower levels of supplemental K (KL_3–KL_6). On the other hand, in terms of overall water consumption, the KL_1 treatment plot came out on top with 281 mm, while the KL_2 plot came in second with 175 mm. The incorporation of extra K fertilizer with KL_2 treatment led to a reduction in overall water consumption as a result of diminished SMD. The WUE fluctuated between 4.73 and 8.14 kg ha^{-1} mm^{-1}, influenced by the amounts of K fertilizer and the GY of mungbean across different water regimes. The maximum WUE (8.14 kg ha^{-1} mm^{-1}) was recorded in the KL_7 treatment, with a GY of 1094 kg ha^{-1}. This high WUE can be attributed to optimal water use that supported moderate GY through effective water utilization. The KL_2 treatment resulted in the lowest WUE (4.73 kg ha^{-1} mm^{-1}) and GY (825 kg ha^{-1}), whereas the KL_1 treatment followed closely behind with 5.01 kg ha^{-1} mm^{-1}.

The study revealed that WS significantly reduced Chl content in mungbean, whereas potassium (K) fertilization notably mitigated these effects (Table 4). Among treatments, the highest Chl-a content was recorded in the KL_1 treatment, while the lowest was observed in the KL_2 treatment. Incremental increases in K fertilizer application from 25% to 125% of the RKF rate (KL_3–KL_7) significantly enhanced the Chl-a content, ranging from 1.63 to 1.76 mg g^{-1} FW. Notably, the WS-tolerant genotype G1 maintained higher Chl-a content than G2, while smaller declines under WS. Genotype G2, although more responsive to K, exhibited greater sensitivity to stress. These findings underscore the protective role of K in preserving Chl-a content under drought, especially in tolerant genotypes. Concerning the interaction between

TABLE 4 Effect of additional K fertilization with recommended K fertilization (RKF) on the chlorophyll content (mg g^{-1} FW) at the pod developing stage (50 days after sowing [DAS]) of mungbean genotypes under WS.

Treatments	Chlorophyll a	Chlorophyll b	Total chlorophyll	Chlorophyll a/b ratio
Potassium fertilization levels (KL)				
KL_1	1.84a	0.83a	2.67a	2.22c
KL_2	1.55d	0.60d	2.14e	2.61a
KL_3	1.63cd	0.64d	2.27de	2.56ab
KL_4	1.65c	0.71c	2.35cd	2.33bc
KL_5	1.69bc	0.73bc	2.43bc	2.31bc
KL_6	1.72bc	0.76bc	2.48bc	2.26c
KL_7	1.76ab	0.79ab	2.54ab	2.26c
CV (%)	6.15	9.06	6.01	12.28
LSD (0.05)	0.09	0.06	0.13	0.26
LS	***	***	***	*
Mungbean genotypes				
BMX-08010-2 (G1)	1.72a	0.74a	2.46a	2.34a
BARI Mung-1 (G2)	1.66b	0.70b	2.36b	2.39a
CV (%)	4.72	7.02	5.23	6.99
LSD (0.05)	0.04	0.02	0.06	0.07
LS	**	***	***	NS
Interactions				
LS	NS	NS	NS	NS

Note: The lowercase letters indicate the results of mean separation using the least significant difference (LSD) test at $p \leq 0.05$. Means followed by the same letter within a column are not significantly different, while those with different letters differ significantly. KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K; G1 = BMX-08010-2; G2 = BARI Mung-1.

Abbreviations: LS, level of significance; RKF, recommended potassium fertilization.

*, **, *** indicate significance at $p = 0.05$, $p = 0.01$, $p = 0.001$, respectively.

genotype and K levels in Table S1, the Chl-a content in G1 increased by 3.75%, 4.38%, 6.25%, 8.75%, and 11.25% when the K fertilizer was increased at 25%, 50%, 75%, 100%, and 125% (KL_3–KL_7), but for G2 the increasing trend was 7.38%, 8.72%, 12.75%, 14.09%, and 16.11%, respectively. The G1 genotype showed a 14.89% decrease in Chl-a under KL_2 treatment compared to KL_1 treatment, while the G2 genotype showed a 16.76% decline. These findings indicate that Chl-a content was adversely affected by WS, with genotype G1 experiencing less damage than G2.

Similarly, Chl-b content followed a comparable trend: highest under KL_1, lowest under KL_2, and progressively improved with increasing K supplementation. Under WS, KL_7 achieved the highest Chl-b values (up to 0.79 mg g^{-1} FW), with G1 again performing better than G2 genotype. Chl-b was found to be more sensitive to WS than Chl-a, but both genotypes benefited from additional K, reflecting K's role in maintaining genotype stability under stress. Specifically, G1 showed increases of 6.35%, 14.29%, 17.46%, 23.81%, and 26.98%, while G2 showed increases of 8.93%, 23.21%, 28.57%, 33.93%, and 37.50%, respectively (Table S1). Compared to KL_2, the KL_1 treatment increased Chl-b content by 36.51% and 42.86% in G1 and G2, respectively. Chl-b was found to be more susceptible to WS than Chl-a. The results indicate that WS negatively affected Chl-b content, but the application of K reduced these adverse effects.

The Chl-a/b ratio was significantly influenced by WS and additional K fertilization, according to data in Table 4. Interestingly, the highest Chl-a/b ratios were observed under WS conditions, in contrast to the trends seen for individual Chl-a and Chl-b levels. This inverse pattern suggests that WS disproportionately affects Chl-b content. However, applying additional K fertilizer at rates of 25%, 50%, 75%, 100%, and 125% in KL_3–KL_7 treatments under WS gradually decreased the Chl-a/b ratio, indicating a more balanced restoration of both genotype types. Although genotype differences were not statistically significant, G2 exhibited a slightly higher Chl-a/b ratio than G1 across treatments, further highlighting its greater sensitivity to WS and stronger response to K.

The TChl content was significantly affected by WS and different K levels in mungbean genotypes (Table 4). The highest TChl content was recorded under the WW condition (KL_1), while the lowest occurred under WS without additional K (KL_2), confirming the suppressive effect of WS on Chl

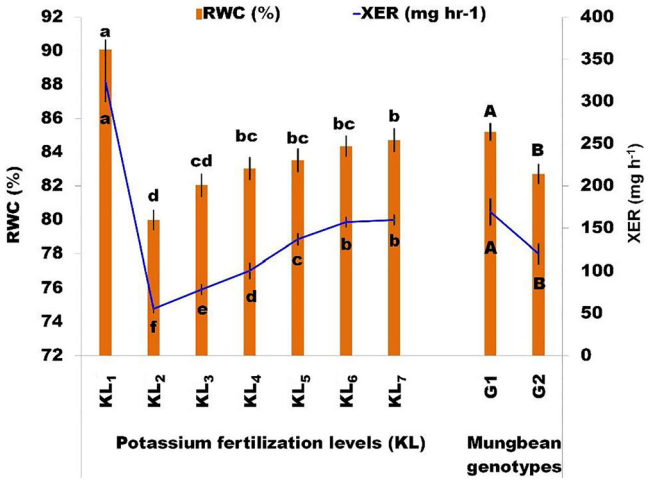


FIGURE 3 Effect of additional K fertilization with recommended K fertilization (RKF) on the relative water content (RWC) and xylem exudation rate (XER) at the pod developing stage (50 days after sowing [DAS]) of mungbean genotypes under water stress, where KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K; G1 = BMX-08010-2; G2 = BARI Mung-1. WS, water stress; WW, well-watered. Lowercase letters indicate significant differences among treatments within the same genotype based on the least signficant difference (LSD) test at $p \leq 0.05$. Uppercase letters indicate significant differences between genotypes for the same treatment at $p \leq 0.05$. Means followed by the same letter are not significantly different, whereas those with different letters differ significantly.

synthesis. However, increasing K fertilization (KL_3–KL_7) under WS significantly increased TChl levels, ranging from 2.27 to 2.54 mg g^{-1} FW. This recovery highlights the role of K in stabilizing Chl and maintaining photosynthesis capacity under stress. Among the mungbean genotypes, G1 exhibited higher TChl content compared to G2. Regarding the interaction effect, the application of additional K fertilizer at rates of 25%, 50%, 75%, 100%, and 125% (KL_3–KL_7) increased TChl content to 2.33, 2.39, 2.45, 2.52, and 2.57 mg g^{-1} FW in G1, and 2.21, 2.32, 2.41, 2.44, and 2.51 mg g^{-1} FW in G2, respectively (Table S1). These results demonstrate that Chl content declined under WS conditions, but increasing K fertilizer levels improved TChl content, likely due to the stabilizing effect of K on Chl.

The RWC was significantly reduced in mungbean genotypes under WS conditions compared to the WW condition (Figure 3). However, it can be seen from Table S1 that the application of additional K improved RWC under WS in both genotypes. Genotype G1 maintained a higher RWC than genotype G2, with G1 showing a minimum reduction in RWC under WS conditions with additional K fertilization compared to the WW condition, highlighting its tolerance to WS. In contrast, genotype G2 exhibited a higher reduction in RWC under WS, reflecting its higher sensitivity to stress. In addition, the RWC of mungbean plants was enhanced by 2.58%, 3.81%, 4.41%, 5.48%, and 5.93% for the treatments KL_3-KL_7 when extra K fertilizer was applied under WS conditions (Figure 2). Under WW (KL_1) conditions, RWC was 12.63% higher compared to WS (KL_2).

In this experiment, WS significantly reduced the XER in both mungbean genotypes at 50 DAS. However, the application of additional K fertilizer improved XER (Figure 3; Table S1). The rise in transpiration rates is likely caused by the function of K in encouraging root development. This, in turn, allows plants to absorb more water and nutrients from deeper soil layers, increasing soil MC, which subsequently enhances plant growth (especially leaf area). The application of additional K fertilizer with RKF levels (KL_3–KL_7) under WS increased XER by 41%, 81%, 147%, 183%, and 188%, respectively (Figure 3). In comparison, the non-stress treatment plot (KL_1) exhibited a 485% higher XER than the WS treatment plot (KL_2). Genotype G1 demonstrated a significantly higher XER than genotype G2, indicating that G2 was more adversely affected by WS and absorbed less water than G1.

The WS and K fertilization had significant effects on the MSI in mungbean genotypes (Figure 4; Table S2). In this study, the KL_2 treatment reduced MSI by 13.55% compared to KL_1 (Figure 4). However, increasing K fertilization with RKF levels (KL_3–KL_7) significantly improved MSI under WS conditions, likely due to the role of K in mitigating excess ROS production. The KL_3–KL_7 treatments increased MSI by 2.57%, 5.40%, 7.45%, 9.64%, and 10.40%, respectively (Figure 4). In terms of MSI among the genotypes, G1 showed a higher level of tolerance to WS (81.92%) than G2 (77.9%). In contrast, G2 was identified as a WS-susceptible genotype.

3.3 | Biochemical traits

The proline content exhibited significant variation in response to increasing K fertilizer levels and between mungbean genotypes (Figure 5; Table S2). The results indicated that proline accumulation was significantly higher under WS conditions compared to WW conditions. However, the data also revealed that increasing levels of K fertilizer substantially reduced proline accumulation under WS conditions. The highest proline content (0.53 mg g^{-1} FW) was recorded under WS with the recommended K fertilizer treatment (KL_2), compared to 0.29 mg g^{-1} FW under WW with the recommended K fertilizer (KL_1). Application of additional K fertilizer under WS conditions at 25%, 50%, 75%, 100%, and 125% of the recommended dose (KL_3–KL_7) significantly reduced proline content by 11%, 19%, 26%, 30%, and 34%, respectively (Figure 5). This suggests that K alleviates the effects of WS. Between the genotypes, the mean proline accumulation was

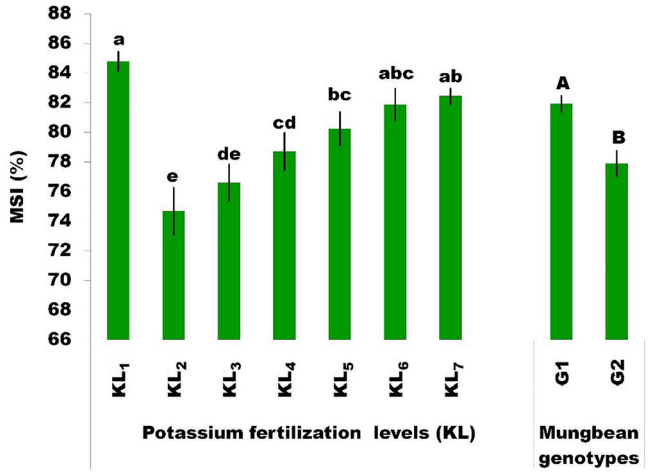


FIGURE 4 Effect of additional K fertilization with recommended K fertilization (RKF) on the membrane stability index (MSI) at the pod developing stage (50 days after sowing [DAS]) of mungbean genotypes under water stress, where KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K; G1 = BMX-08010-2; G2 = BARI Mung-1. WS, water stress; WW, well-watered. Lowercase letters indicate significant differences among treatments within the same genotype based on the least signficant difference (LSD) test at $p \leq 0.05$. Uppercase letters indicate significant differences between genotypes for the same treatment at $p \leq 0.05$. Means followed by the same letter are not significantly different, whereas those with different letters differ significantly.

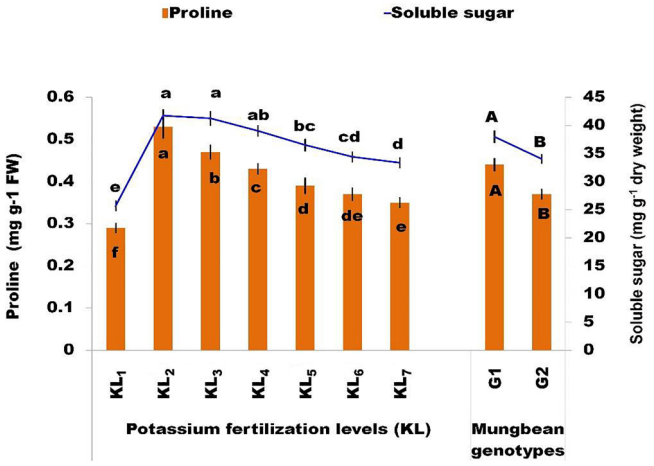


FIGURE 5 Effect of additional K fertilization with recommended K fertilization (RKF) on the proline (mg g^{-1} FW) and soluble sugar content (mg g^{-1} dry weight) at the pod developing stage (45 days after sowing [DAS]) of mungbean genotypes under water stress, where KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K; G1 = BMX-08010-2; G2 = BARI Mung-1. WS, water stress; WW, well-watered. Lowercase letters indicate significant differences among treatments within the same genotype based on the least signficant difference (LSD) test at $p \leq 0.05$. Uppercase letters indicate significant differences between genotypes for the same treatment at $p \leq 0.05$. Means followed by the same letter are not significantly different, whereas those with different letters differ significantly.

higher in genotype G1 (0.44 mg g^{-1} FW) compared to G2 (0.37 mg g^{-1} FW), indicating that G1 was more tolerant to WS.

Regarding SS content, it was significantly higher in both mungbean genotypes under WS compared to WW conditions. Additionally, the application of K fertilizer reduced SS content, indicating that K mitigated the effects of WS (Figure 5; Table S2). The lowest SS content (25.70 mg g^{-1} DW) was recorded in the KL_1 treatment, while the highest SS content (41.75 mg g^{-1} DW) was observed in the KL_2 treatment. The KL_2 treatment resulted in a 62.45% increase in SS compared to KL_1. Increasing K fertilizer levels at 25%, 50%, 75%, 100%, and 125% of the RKF under WS (KL_3–KL_7) significantly decreased SS content by 1.20%, 6.47%, 12.57%, 17.60%, and 20.12%, respectively (Figure 5). Among the genotypes, G1 produced higher SS content (37.99 mg g^{-1} DW) compared to G2 (34.01 mg g^{-1} DW).

3.4 | Canopy temperature depression

The CTD was measured as the difference between air temperature and canopy temperature at the flowering and pod-filling stages (Figure 6; Table S2). The results revealed that mungbean grown under KL_2 recorded the minimum CTD (−2.13°C and 4.02°C) compared to KL_1 (−4.35°C and −6.67°C) at the flowering and pod-filling stages, respectively. The use of the additional K fertilizer with KL_2 increased the CTD. Notably, the highest CTD (−4.12°C and −6.24°C) was observed with the application of 125% K fertilizer (KL_7), compared to KL_2 treatment. This improvement may be attributed to the 125% K level, which enhanced canopy coverage and root growth, leading to greater water consumption and a higher transpiration rate, thereby lowering canopy temperature and resulting in a higher CTD. Between the genotypes, G1 exhibited higher CTD (−3.90°C and −6.09°C), while G2 recorded comparatively lower CTD (−3.37°C and −5.14°C). This difference can be explained by the larger leaf area and more extensive root growth in G1, which likely contributed to a higher transpiration rate, resulting in a lower canopy temperature.

3.5 | Crop harvest output

Biological yield (BY) varied significantly among mungbean genotypes, K levels, and their interactions (Figure 7; Table

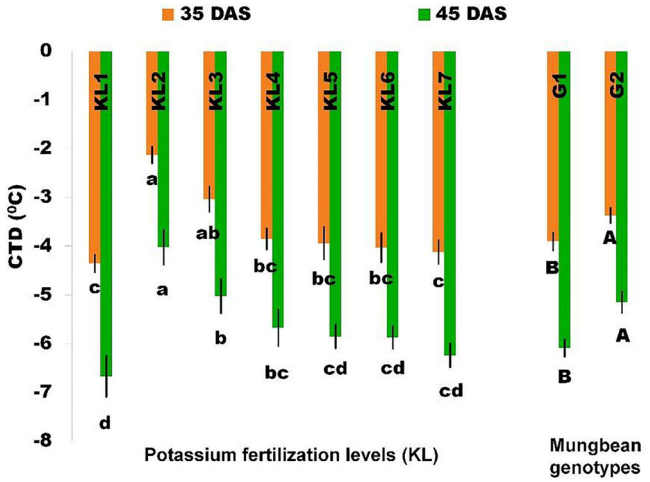


FIGURE 6 Effect of additional K fertilization with recommended K fertilization (RKF) on the canopy temperature depression (CTD) at 35 and 45 days after sowing (DAS) of mungbean genotypes under water stress, where KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K; G1 = BMX-08010-2; G2 = BARI Mung-1. WS, water stress; WW, well-watered. Lowercase letters indicate significant differences among treatments within the same genotype based on the least signficant difference (LSD) test at $p \leq 0.05$. Uppercase letters indicate significant differences between genotypes for the same treatment at $p \leq 0.05$. Means followed by the same letter are not significantly different, whereas those with different letters differ significantly.

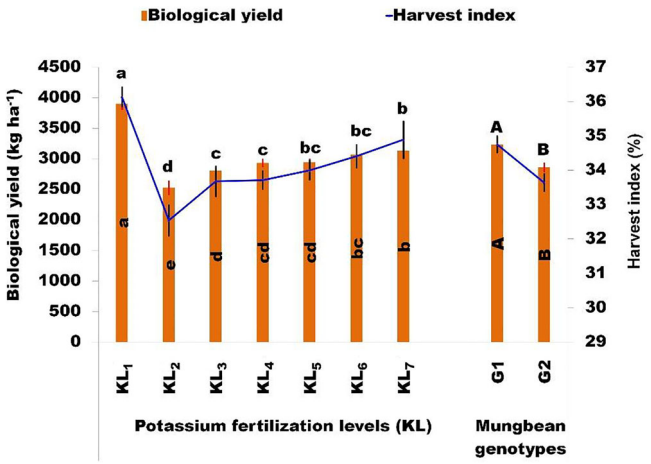


FIGURE 7 Effect of additional K fertilization on the biological yield (kg ha^{-1}) and harvest index (%) at harvest of mungbean genotypes under water stress. KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K; G1 = BMX-08010-2; G2 = BARI Mung-1. RKF, recommended potassium fertilization; WS, water stress; WW, well-watered. Lowercase letters indicate significant differences among treatments within the same genotype based on the least signficant difference (LSD) test at $p \leq 0.05$. Uppercase letters indicate significant differences between genotypes for the same treatment at $p \leq 0.05$. Means followed by the same letter are not significantly different, whereas those with different letters differ significantly.

S2). The maximum BY (3899 kg ha^{-1}) was recorded under the KL_1 treatment, while the lowest BY (2526 kg ha^{-1}) was obtained under KL_2. Regarding the results, BY was reduced by 35.23% under KL_2 compared to KL_1. Nevertheless, under WS conditions, the application of extra K fertilizer at 25%, 50%, 75%, 100%, and 125% of the RKF resulted in a BY increase for KL_3–KL_7. The highest BY (3130 kg ha^{-1}) was observed under the KL_7 treatment, which received the highest K level (125%). An upward trend in GY contributed to the overall increase in BY under the KL_2 condition with extra K fertilization. Among the genotypes, G1 produced the highest BY (3228 kg ha^{-1}), while G2 produced 2858 kg ha^{-1}, which was 11% lower than G1. The results demonstrated that each increase in K level led to a noticeable improvement in BY.

Genotypes and potassium (K) levels had a significant impact on the harvest index (HI) (Figure 7), though their interaction showed no significant variation (Table S2). The results showed that the highest HI (36.14%) was recorded in plots receiving WW conditions with the RKF (KL_1), while the lowest HI (32.54%) was observed in plots under WS with RKF (KL_2). This indicated that HI was reduced under WS compared to WW conditions. However, the application of additional K fertilizer (KL_3–KL_7) increased HI, with the highest HI (34.89%) observed under KL_7 treatment, which received 125% K under WS conditions. This was followed by treatments with lower K levels under the same stress conditions. Genotype G1 produced the highest HI (34.75%) compared to G2 (33.64%).

Mungbean pods were harvested three times, and yields were adjusted for the respective harvesting times and then pooled. Both the individual genotypes of mungbeans and the interaction between them and increasing K levels significantly affected grain production throughout all harvests and the pooled GY (Figure 8; Table S3). Nevertheless, the WS condition considerably decreased grain output in the two genotypes. GY was highest with the KL_1 treatment at the third picking, then the first and second pickings. For the other treatments (KL_2–KL_7), the highest GY was observed in the first picking, followed by the third and second pickings. GY was highest with the KL_1 treatment at the third picking, then the first and second pickings. When it came to the other treatments (KL_2–KL_7), the first picking produced the most grain, followed by the third and second pickings. A combination of RKF and a higher K fertilizer application under WS conditions increased GY across all harvests and the pooled yield. The pooled yields were higher when the K levels were increased by 25%, 50%, 75%, 100%, and 125% (KL_3-KL_7) than KL_2 treatments under

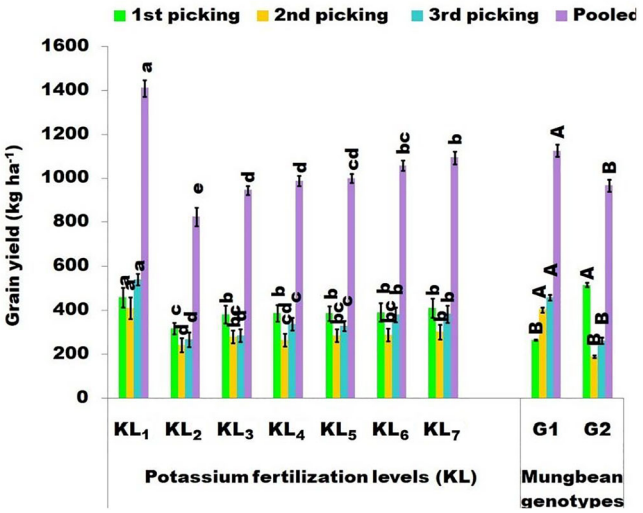


FIGURE 8 Impact of supplementary K fertilization with recommended K fertilization (RKF) on water-stressed mung bean genotype yields (kg ha^{-1}). KL_1 = WW + RKF (18 kg K ha^{-1}); KL_2 = WS + RKF (18 kg K ha^{-1}); KL_3 = WS + RKF + 25% additional K; KL_4 = WS + RKF + 50% additional K; KL_5 = WS + RKF + 75% additional K; KL_6 = WS + RKF + 100% additional K; KL_7 = WS + RKF + 125% additional K; G1 = BMX-08010-2; G2 = BARI Mung-1. WS, water stress; WW, well-watered. Lowercase letters indicate significant differences among treatments within the same genotype based on the least signficant difference (LSD) test at $p \leq 0.05$. Uppercase letters indicate significant differences between genotypes for the same treatment at $p \leq 0.05$. Means followed by the same letter are not significantly different, whereas those with different letters differ significantly.

moist soil conditions. When compared to mungbean plants treated with RKF alone (KL_2), those treated with 125% more K and RKF under WS (KL_7) conditions had a 32.52% increase in grain production. Possible causes of this production boost include better water status, improved plant development, a larger leaf area index, and total dry matter. GY was enhanced as a result of these factors, which caused plants to grow greater in height, produce more pods per plant, and lengthen pod development. From a genotypic perspective, G2 produced the highest GY in the first picking, followed by the third and second pickings, while G1 produced the highest yield in the third picking, followed by the second and first pickings. However, G1 outperformed G2 by 16% in total GY. The G2 (stress-sensitive) genotype was less responsive to K fertilization than the G1 (moderate stress-tolerant) genotype when it came to improving GY under WS conditions. Improvements in plant height, pods per plant, and pod length were the main factors linked to an increase in GYs. It is important to note that the K content in the experimental soil was medium (Table 1), and therefore, the application of higher K doses likely contributed to the increased GY.

4 | DISCUSSION

The findings of the study indicate that mungbean plants are highly vulnerable to WS, particularly during the pre-flowering stage and subsequent growth stages, consistent with earlier reports (Fooladivanda et al., 2014; M. S. Islam, 2001). However, the application of additional K fertilizer in combination with the recommended fertilizer dose (RKF) under WS conditions significantly improved soil MC (Figure 1). This is in line with earlier studies highlighting the role of K in maintaining plant enzyme activity and supporting photosynthesis (Cakmak, 2005). Increased K levels also promoted plant leaf area development (M. R. Islam et al., 2024), which likely contributed to reduced soil moisture loss through evaporation and supported deeper root growth, thereby enhancing water uptake. These findings suggest that K supplementation can effectively enhance soil moisture retention under drought and WS conditions. Furthermore, the findings reaffirm that WS during the flowering and pod-filling stages severely and drastically reduces GY and WUE in mungbean (Eroğlu & Önder, 2023; Thomas et al., 2004).

Potassium (K) application had a significant positive effect on the physio-biochemical traits of mungbean under WS conditions. One of the most notable responses was observed in leaf Chl content, a sensitive indicator of plant health under abiotic stresses (Bano et al., 2021). In this study, Chl content declined under WS conditions, but the reduction was less severe in the WS-tolerant mungbean genotype compared to the susceptible one (Table 4), consistent with findings by M. R. Islam et al. (2022). This decline in Chl content is commonly linked to an imbalance between degradation and biosynthesis, with stress accelerating chlorophyll breakdown (Yang et al., 2021). In addition, WS at any growth stage led to a reduction in photosynthetic pigments, including Chl a, Chl b, and carotenoids in mungbean leaves (M. R. Islam et al., 2021, 2022). Furthermore, the negative impact on Chl content due to WS could be recovered by K application, as highlighted by previous studies (Zarifinia et al., 2012).

In this study, the additional application of K fertilizer under WS significantly enhanced performance in both RWC and XER, particularly in the drought-tolerant genotype (Figure 2). RWC is an integrative indicator of a plant's hydration status and its ability to maintain physiological function during WS (Tamanna et al., 2023). Numerous studies have shown that the K fertilizer plays a vital role in sustaining leaf water content of leguminous crops, thereby enhancing their tolerance to WS (Kataria & Singh, 2022; Majeed et al., 2016). This effect is largely attributed to K's function in osmotic adjustment, turgor pressure, and support of key physiological processes such as photosynthesis and stomatal conductance (Hasanuzzaman et al., 2018; Wang et al., 2013). Evidence also suggests that K application improves RWC in various crops, with maximum effects observed at moderate to high K levels (Sustr et al.,

2019). WS-susceptible genotypes generally show a sharper decline in water potential and RWC than in WS-tolerant ones, highlighting their limited capacity to maintain water balance under stress (Chowdhury et al., 2021; Tamanna et al., 2023). This variation is often attributed to differences in stomatal regulation and root water uptake efficiency, as observed in crops like mungbean (Bagheri et al., 2023; M. R. Islam et al., 2021, 2022). WS significantly reduced XER, a physiological indicator closely tied to transpiration and root activity. However, increasing K levels helped improve XER under stress. These findings align with previous studies showing that XER is typically higher under WW conditions and declines with increasing WS severity (M. R. Islam et al., 2021). Thus, XER can serve as a reliable tool to assess WS tolerance among genotypes.

MSI was notably affected by WS, showing a significant improvement observed at higher K levels (Figure 3). Among the genotypes, the WS-tolerant G1 exhibited the highest MSI under WS, suggesting a stronger protective response compared to the sensitive G2. MSI is a critical early indicator of WS tolerance, as it reflects a plant's ability to maintain membrane integrity under stress. Plants with higher MSI values are better equipped to withstand oxidative damage, making this trait a useful benchmark for evaluating stress resilience.

A plant's ability to accumulate proline is a very significant physiological marker of its response to WS or WS. Plants accumulate higher levels of proline to survive under WS conditions. The results show that proline content was significantly higher under WS (KL_2) than WW conditions (KL_1). However, increasing K levels (KL_3–KL_7) gradually reduced proline accumulation (Figure 4). This reduction may be attributed to decreased leaf water potential and the accumulation of free proline under WS conditions (Bangar et al., 2019). Proline accumulation varies with leaf age, leaf position, and plant age. In addition, proline plays a major role as an electron receptor and enhances the plant's damage-repairing ability by increasing antioxidant activity during WS (Yaish, 2015). Under WS conditions, proline accumulation is greater than that of other amino acids, making it a reliable measure for screening WS-tolerant genotypes (Chauhan et al., 2023).

Furthermore, the accumulation of SSs under WS is a well-recognized adaptive mechanism that contributes to osmotic adjustment in plants (Rosa et al., 2009). This physiological response not only helps maintain cellular water balance but also supports growth and development by regulating carbohydrate metabolism during abiotic stresses (Sami et al., 2016). In this study, SS levels serve as an energy reserve for critical functions such as seed filling, especially under WS conditions when normal metabolic pathways are disrupted. These findings are in agreement with those of Choudhury (2009), who reported increased SS content in French bean leaves under WS conditions.

CTD is widely used to measure WS and heat tolerance in plants. Under stressful environmental conditions, reduced stomatal conductance and declining soil MC lead to an increase in canopy temperature (Rebetzke et al., 2012). In this study, CTD values under WS conditions (KL_2) were approximately 51% and 40% lower than those under WW conditions (KL_1) at 35 and 45 DAS, respectively (Figure 5). Typically, higher CTD values are associated with improved GY under WS conditions (Deery et al., 2016). Previous studies have shown strong correlations between CTD and key physiological traits, such as transpiration rates (Hou et al., 2019), leaf water potential (Balota et al., 2007), root access to deep soil moisture, biomass production, and GY (Reynolds et al., 1994) under WS conditions. Moreover, water-stress-sensitive genotypes experience relatively greater yield losses under WS conditions.

In the current study, WS led to significant reductions in BY (35%), HI (10%), and pooled GY (41%) under the KL_2 treatment compared to WW conditions (KL_1). However, these declines were effectively mitigated by the application of additional K fertilizer in treatments KL_3–KL_7, with the highest improvements observed at 125% K supplementation (KL7) under WS (Figure 6; Table 4). The WS-tolerant genotype G1 outperformed G2 in all yield-related traits for the BY, HI, and pooled GY traits. These improvements can be attributed to K's critical role in sustaining photosynthate production, which is typically reduced under WS conditions due to impaired photosynthesis and limited assimilate translocation. The K remarkably increased the GY of mungbean. Research has shown that K is essential for increasing grain output since it has a beneficial effect on both pod quantity and grain per pod. Drought stress during stem elongation and flowering stages can significantly reduce GY due to a decline in the development of reproductive organs. Similarly, stress during grain filling reduces GY by lowering 1000-grain weight (Farooq et al., 2017). Earlier findings indicated that K application not only enhances the availability of other nutrients but also increases the photosynthesis rate in mungbean, resulting in higher GY (S. Kumar et al., 2018). It is probable that the increased grain production seen under WS conditions after K fertilization is a result of improved water status in the plants treated with K. This is supported by a considerably higher RWC, which in turn has a good effect on many physiological processes. In addition, growing high-yielding crop types and increased cropping intensity both accelerate soil K depletion. Since there is no natural replenishment of K in soils, its declining levels negatively affect crop yield and quality (Hassan et al., 2023).

5 | CONCLUSION

The results indicate that supplementing the recommended potassium (K) fertilizer dose with additional K is the most effective strategy for achieving the highest safe yield of mungbean. Under WS conditions, the application of

additional K fertilizer significantly mitigated the adverse effects of WS on WUE, key physio-biochemical traits (Chl content, RWC, XER, MSI, proline, SS), plant growth, and seed yield of mungbean. Notably, the use of 125% additional K fertilizer with the recommended dose (KL_7) resulted in a 32.52% increase in GY, highlighting its potential to alleviate the negative impacts of WS. Among the two genotypes studied, the genotype G1 demonstrated greater tolerance to WS compared to G2, consistently outperforming it across all physio-biochemical, biological, and seed yield traits. Collectively, these findings support the recommendation that mungbean cultivation under WS conditions requires additional K supplementation to minimize drought-induced yield losses. Furthermore, the balanced and appropriate application of K in conjunction with other essential nutrients is crucial for ensuring sustainable productivity and quality in mungbean cultivation. Importantly, these nutrient management strategies align well with the broader frameworks of climate-smart agriculture and sustainable intensification, which aim to enhance crop yields sustainability while conserving resources, improving soil health, and reducing environmental impacts.

AUTHOR CONTRIBUTIONS

Mohammad Rafiqul Islam: Conceptualization; formal analysis; investigation; methodology; software; validation; visualization; writing—original draft; writing—review and editing. **Mohammad Ashraful Alam**: Data curation; visualization. **Md Mashiur Rahman**: Software; visualization; writing—original draft; writing—review and editing. **Mohammad Shahin-Uz-Zaman**: Visualization; writing—review and editing. **Md. Shahin Iqbal**: Visualization; writing—review and editing. **Ayman El-Sabagh**: Visualization; writing—original draft; writing—review and editing. **Hassan Nuur Ismaan**: Visualization; writing—review and editing. **Md Ariful Islam**: Visualization; writing—original draft; writing—review and editing. **Naznin Sultana**: Visualization; writing—original draft; writing—review and editing. **Mohammad Sohidul Islam**: Conceptualization; formal analysis; investigation; methodology; software; supervision; validation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data are included in the manuscript and/or supporting information.

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