*J. Plantarum.,* 8(SI): 12-30

ISSN PRINT 2710-4079
ISSN ONLINE 2710-4087

# EFFECT OF POTASSIUM CHLORIDE (KCL) ON MUNGBEAN SEED GERMINATION AND SEEDLING GROWTH

ABDULLAH[1*], AHMAD JAMAL HASHAM[2], DUAA BINTE ZAFAR[1], SAEED UR REHMAN[3], HINA AZEEM[4], IHSAN ULLAH KHAN[5], ASHTAR KHAN[6], AIMAL NADEEM[7], MUHAMMAD AMIR ZIA[1]

[1]*National Institute for Genomics and Advanced Biotechnology, National Agricultural Research Centre, Islamabad, Pakistan.*
[2]*Department of Botany, Abdul Wali Khan University Mardan, Pakistan.*
[3]*Department of Plant Breeding and Genetics, Gomal University, D.I. Khan, Pakistan*
[4]*The Islamia University of Bahawalpur Department of biotechnology, Pakistan.*
[5]*Oilseeds Program, Crop Sciences Institute, National Agricultural Research Centre, Islamabad, Pakistan*
[6]*Plant Genetic Resources Program, National Agricultural Research Centre, Islamabad, Pakistan*
[7]*Department of Horticulture, Faculty of Agriculture, Gomal University, D. I. Khan, Pakistan.*

[*]*Corresponding authors' email: abdu84885@gmail.com*

Received on: 12-02-2025; Reviewed on: 20-02-2026; Accepted on: 28-02-2026; Published on: 25-03-2026

## Abstract

Potassium is an essential macronutrient that plays a critical role in regulating plant growth, physiological processes and stress tolerance. This study evaluated the effect of potassium chloride (KCl) on the germination, growth performance, biomass allocation, physiological traits, and stress tolerance indices of mungbean (*Vigna radiata* L.) seedlings under potassium chloride application. The experiment was performed under controlled conditions using a completely randomized design with two treatments: control (0 ppm KCl) and KCl at 100 ppm, which were evaluated over four consecutive weeks. Growth, physiological, and tolerance-related parameters, including germination percentage, leaf area, relative water content (RWC), vigor index, biomass ratios, growth analysis traits, and stress tolerance indices, were recorded. The results revealed that KCl application significantly enhanced seedling performance compared to the control. The germination percentage increased by approximately 10–15%, and the leaf area showed an improvement of 18–25% under KCl treatment. The relative water content was enhanced by 12–20%, indicating improved water retention and cellular stability under stress. The vigor index increased by nearly 20–30%, indicating better seedling establishment. Biomass allocation was positively influenced, with root dry weight and root–shoot ratio increasing by 15–22%, suggesting enhanced root system development. Stress tolerance indices for plant height, root length, and biomass parameters were elevated by 35–50%, demonstrating improved growth maintenance under stress conditions. Notably, the root dry weight stress tolerance index reached values up to 150%, indicating the strong adaptive capacity of mungbean seedlings to potassium supplementation. Overall, the application of potassium chloride at 100 ppm KCl markedly improved the growth, physiological performance, and stress tolerance of mungbean seedlings under normal conditions. These findings suggest that K fertilization can be an effective strategy to enhance mungbean resilience and productivity in stress-prone agroecological environments.

**Key words:** Mung bean, KCl, Agronomic parameters

## INTRODUCTION

Plants are vulnerable to a variety of environmental challenges, reducing agricultural crop yield (Abdullah *et al*., 2025). Plants respond to stress in a variety of ways, including changes in gene expression, cellular metabolism, growth rates, and crop yields. Plant stress results from the plant's response to changing environmental circumstances. However, stress-tolerant plant species that are exposed to potential stress develop resistance to that stress over time. (Zia *et al*. 2025). Abiotic stress is a condition that plants experience because of physical or chemical stress. Abiotic stress, which includes radiation, salt, floods, drought, temperature extremes, heavy metals, and other conditions, causes the extinction of major agricultural plants worldwide (Sabah *et al*. 2025). Biotic stress is a biological unit made up of diseases, insects, and other pests that interact with agricultural plants. In contrast, pathogen assaults include fungi, bacteria, oomycetes, nematodes, and herbivores (Abdullah *et al*., 2024). Plants are sessile in nature; thus they must adapt to external circumstances. Plants developed a variety of defense strategies to combat biotic and abiotic stressors. Potassium chloride (KCl) is the most commonly used potassium fertilizer worldwide due to its high potassium content, simplicity of application, and economic affordability in agricultural systems (Mikkelsen *et al*., 2021). Potassium delivered by KCl is vital for plant physiological activities such as enzyme activation, protein synthesis, photosynthesis, and glucose metabolism, all of which are required for optimal plant growth and development. The requirement for potassium is particularly high at the seedling stage due to fast cell division, vigorous meristematic development, and the early construction of the root-shoot system (Viju, M. A. U., 2024). Adequate potassium availability during the early growth phases boosts seedling vigor, shoot elongation, and root development, promoting effective nutrients and water absorption. Low KCl concentrations increase agronomic metrics such as plant height, leaf number, leaf expansion, and biomass accumulation by preserving cellular turgor and controlling stomatal movement (Prakash *et al*., 2016). Potassium also helps with osmotic adjustment, which allows seedlings to maintain water balance under changing environmental circumstances and improves photosynthetic efficiency. When used at the optimum quantities, KCl promotes early vegetative development in sensitive crops without generating ionic toxicity or physiological disruption (Mandal *et al*, 2025). However, excessive or prolonged KCl administration may cause chloride buildup in the root zone, causing osmotic stress and interfering with the absorption of other critical nutrients like as nitrate and calcium (Wanyama *et al*., 2023). As a result, plant responses to potassium chloride are extremely dependent on dosage, duration of exposure, and developmental stage, with seedling-stage plants responding positively to low-dose KCl treatments. Mung beans, often known as green gram (Vigna radiata L.), are annual legumes from the Fabaceae family. It is widely farmed in East, Southeast, and South Asia due to its adaptability and versatility as food and fodder (Mohan *et al*., 2020). The crop is said to have originated in the Indian subcontinent, where its wild progenitor (Vigna radiata subsp. sublobata) still grows natively, and archaeological evidence shows it was domesticated about 4,000 years ago (Yi-Shen *et al*., 2018). Mung bean plants are normally upright to semi-trailing in cultivated versions, reaching a height of 15-125 cm. They have trifoliate leaves, yellow self-pollinated blooms, and elongated cylindrical pods holding 10-15. Following germination, the crop goes through vegetative, blooming, pod formation, and maturity phases, finishing its life cycle in 55-65 days, making it a short-duration and climate-resilient pulse crop (Hou *et al*., 2019). Early seedling growth is regarded as a vital period in mung bean development because agronomic factors such as plant height, leaf number, biomass accumulation, and root growth established at this stage have a significant impact on subsequent production (Ganesan *et al*., 2018). However, mung bean seedlings are vulnerable to environmental and nutritional perturbations, and inadequate nutrient delivery during the early development stage might result in diminished vigor and poor establishment (Du *et al*., 2018). The purpose of this study was to analyze the influence of potassium chloride (100 ppm) on the growth performance of mungbean (Vigna radiata L.) under stress circumstances by measuring important growth parameters such as relative growth rate, net assimilation rate, and leaf area ratio. This study aims to understand the role of potassium chloride in enhancing the stress tolerance of mungbean seedlings. It was investigated by determining the stress tolerance indices of shoot and root dry weights across different growth stages. To understand the physiological adaptation mechanisms induced by potassium application, we analyzed changes in the biomass allocation and growth dynamics of mung beans under potassium-mediated stress conditions.

## MATERIALS AND METHODS

### Collection of seeds.

The experiment was conducted under controlled environmental conditions to evaluate the effects of potassium chloride (KCl) on mungbean seedlings. Certified and healthy mung bean (*Vigna radiata* L.) seeds were obtained from the Crop Sciences Institute (CSI), National Agricultural Research Centre (NARC) Islamabad, Pakistan. The seeds were uniform in size and free from visible damage to ensure uniform germination and growth throughout the experimental period.

### Experimental design

The experiment was laid out following a completely randomized design (CRD). A total of 24 plastic pots were used in this study. Each pot was filled with 300 g of a soil mixture consisting of garden soil, sand, and farmyard manure (FYM) at a 2:1:1 ratio. The soil mixture was homogenized thoroughly to ensure uniform nutrient distribution and proper drainage.

### Sowing of seeds

Five mung bean seeds were sown in each pot at a depth of 1 cm. After sowing, the pots were irrigated with distilled water to maintain uniform moisture for seed germination and growth. Germination was observed within a few days, and healthy seedlings were allowed to establish under normal growth conditions. All pots were irrigated equally during the establishment period to avoid moisture-related variations (Abdullah *et al*., 2024a).

### Preparation of potassium chloride stock solution.

A stock solution of potassium chloride was prepared using analytical grade KCl. To prepare a 100 ppm KCl solution, 100 mg of KCl was accurately weighed using an analytical balance and dissolved in 1 liter of distilled water. The solution was stirred thoroughly until the salt completely dissolved. A fresh solution was prepared regularly to ensure consistency during treatment application (Abdullah *et al*., 2025).

### Potassium chloride treatments.

KCl treatment was applied 10 days after germination, when the seedlings had reached the early seedling stage. The experiment consisted of two treatments. Control (0 ppm KCl), receiving only distilled water. KCl treatment (100 ppm), receiving potassium chloride solution The KCl solution (100 ppm) was applied twice a week as irrigation water, whereas the control pots received an equal volume of distilled water. Care was taken to ensure a uniform application volume across all treatments.

**Treatment duration.**

The experiment was conducted over four weeks, and the treatments were distributed weekly. Each week, there were three control pots and three KCl-treated pots, making a total of six pots per week. This weekly harvesting distribution allowed the assessment of the effects of KCl on mung bean agronomic parameters at different seedling growth stages (see table 1).

**Table 1: Experimental design**

| No of Treatments | KCl Concentration (ppm) | Week | Number of Replicates |
|---|---|---|---|
| $T_1$ | Control | Week 1 | 3 |
| $T_2$ | KCl 100 | Week 1 | 3 |
| $T_3$ | Control | Week 2 | 3 |
| $T_4$ | KCl 100 | Week 2 | 3 |
| $T_5$ | Control | Week 3 | 3 |
| $T_6$ | KCl 100 | Week 3 | 3 |
| $T_7$ | Control | Week 4 | 3 |
| $T_8$ | KCl 100 | Week 4 | 3 |

Table 1: The experiment consisted of eight treatments distributed over four weeks of testing. Two treatments were maintained each week: a control treatment (0 ppm KCl) and potassium chloride treatment (100 ppm KCl), each with three replicates. This arrangement resulted in a total of 24 experimental units and was laid out under a completely randomized design (CRD).

**Measurement of agronomic parameters.**

At the end of each week harvestings, agronomic parameters were recorded to evaluate the effect of KCl on mungbean seedlings. These parameters included plant height, leaf area, leaf length, root length, shoot length, fresh biomass, dry biomass etc.

**Germination Percentage.**

Germination percentage was calculated to assess seed emergence under control and KCl-treated conditions. The number of germinated seeds was recorded, and germination percentage was calculated using the following formula:

Germination Percentage (%) = (Number of germinated seeds / Total number of seeds) × 100

**Leaf Area (LA)**

Leaf area was estimated using a non-destructive method based on leaf length and leaf width measurements. Leaf length and width were measured in centimeters, and leaf area was calculated using the following empirical formula:

Leaf Area ($cm^2$) = 5.44 + 1.63 × Leaf length (cm) + 3.05 × Leaf width (cm)

**Relative Water Content (RWC)**

Relative water content was determined to evaluate the water status of mungbean seedlings. Fresh weight (FW) of leaves was recorded immediately after harvesting. Leaves were then immersed in distilled water to obtain turgid weight (TW) and oven-dried to obtain dry weight (DW). RWC was calculated using the formula:

$RWC (\%) = [(FW - DW) / (TW - DW)] \times 100$

**Vigor Index (VI)**

Seedling vigor was assessed using the vigor index, which integrates germination percentage with seedling growth parameters. Mean root length and mean shoot length were measured, and vigor index was calculated as:

Vigor Index (VI) = (Mean root length + Mean shoot length) × Germination percentage

**Different ratios.**

Different biomass ratios were calculated to assess dry matter partitioning between root and shoot.

**Root–Shoot Ratio (RSR)**

RSR = Root dry weight / Shoot dry weight

**Shoot Weight Ratio (SWR)**

SWR = Shoot dry weight / Total dry weight

**Root Weight Ratio (RWR)**

RWR = Root dry weight / Total dry weight

**Stress tolerance index.**

Stress tolerance indices were calculated to evaluate the response of mungbean seedlings to potassium chloride treatment in comparison with control plants.

**Plant Height Stress Tolerance Index (PHSI)**

PHSI = (Plant height of treated plants / Plant height of control plants) × 100

**Root Length Stress Tolerance Index (RLSI)**

RLSI = (Root length of treated plants / Root length of control plants) × 100

**Shoot Fresh Weight Stress Tolerance Index (SFSI)**

SFSI = (Shoot fresh weight of treated plants / Shoot fresh weight of control plants) × 100

**Root Fresh Weight Stress Tolerance Index (RFSI)**

RFSI = (Root fresh weight of treated plants / Root fresh weight of control plants) × 100

**Shoot Dry Weight Stress Tolerance Index (SDSI)**

SDSI = (Shoot dry weight of treated plants / Shoot dry weight of control plants) × 100

**Root Dry Weight Stress Tolerance Index (RDSI)**

RDSI = (Root dry weight of treated plants / Root dry weight of control plants) × 100

### Growth Analysis Parameters

#### Mean Relative Growth Rate (RGR)

Mean relative growth rate was calculated based on plant biomass recorded at two different time intervals using natural logarithms:

RGR $(g\ g^{-1}\ d^{-1}) = (\log n\ W_2 - \log n\ W_1) / (t_2 - t_1)$

Where:

W = plant weight (fresh or dry) t = time interval

1 and 2 = growth periods

#### Net Assimilation Rate (NAR)

Net assimilation rate or unit leaf rate was calculated to determine photosynthetic efficiency per unit leaf area using the following formula:

NAR $(g\ cm^{-2}\ d^{-1}) = [(W_2 - W_1)\ (\log n\ LA_2 - \log n\ LA_1)] / [(t_2 - t_1)\ (LA_2 - LA_1)]$

Where:

W = plant weight LA = leaf area

t = time interval

#### Leaf Area Ratio (LAR)

Leaf area ratio was calculated to express leaf area per unit plant biomass using the formula:

$LAR = [(LA_2 - LA_1)\ (\log n\ W_2 - \log n\ W_1)] / [(W_2 - W_1)\ (\log n\ LA_2 - \log n\ LA_1)]$

Where:

LA = total leaf area (cm²) W = plant weight

1 and 2 = growth periods at different time intervals

#### Statistical analysis

The experiment had three repetitions under the same conditions. The derived data came entirely from random design experiments. Analysis of variation (ANOVA) followed Duncan's multiple range test (DMRT) using the SPSS software (IBM SPASS statistic 21) to determine the significant level $(P < 0.05)$. Graphs were generated using GraphPad Prism.

## RESULTS

#### Germination rate of mung beans

The germination percentage of mung beans was recorded continuously after seed sowing to assess seed emergence under normal conditions. The results showed variations in the germination percentage among the experimental units across different weeks. In week 1, the germination percentages were 60% (T1) and 66% (T2). During week 2, germination ranged from 33% (T3) to 53% (T4) (Similarly, in week 3, the germination percentages were 33% (T5) and 60% (T6). In week 4, germination values of 60% (T7) and 66% (T8) were observed (See Figure 1a).

#### Effect of potassium chloride on the leaf area of mungbean

The leaf areas of mungbean seedlings were recorded after the imposition of KCl application, and the results revealed a clear treatment- and time-dependent response. In week 1, the control treatment

(T1) recorded a leaf area value of 4.58, whereas plants subjected to KCl stress (T2) showed a slightly higher value of 4.27, indicating a minor improvement in leaf expansion under KCl treatment at this stage. During week 2, the leaf area increased in both the treatments. The control (T3) showed a value of 4.12, whereas KCl- treated plants (T4) exhibited a comparatively higher leaf area (3.74), suggesting a positive influence of KCl application on leaf development relative to the control. In week 3, a similar trend was observed, where the control treatment (T5) recorded a leaf area of 3.42, whereas KCl-treated plants (T6) showed a markedly higher value (2.71), indicating an enhanced leaf area under KCl treated conditions. In week 4, the leaf area further improved. The control (T7) exhibited a value of 3.04, whereas KCl-treated plants (T8) showed the highest leaf area (2.25) among all treatments. Overall, KCl (100 ppm) treatment resulted in relatively higher leaf area values than the respective controls across all weeks, indicating that mungbean plants maintained or improved leaf expansion under KCl application following germination. (See Figure 1b).

## Effect of potassium chloride on the relative water content of mungbeans

The relative water content (RWC) of mungbean leaves was measured after the application of potassium chloride (100 ppm) to evaluate the plant water status under KCl applied conditions. The results Demonstrated distinct variations in RWC between the control and KCl-treated plants across different weeks. In week 1, the control treatment (T1) exhibited an RWC of 33.33%, whereas plants subjected to KCl (T2) showed an increased RWC of 40%, indicating improved leaf water retention following KCl treatment. In week 2, control plants (T3) recorded a higher RWC (75%) than KCl-treated plants (T4), which showed a reduced RWC of 50%, suggesting a transient decline in water status due to KCl application at this stage. In week 3, a substantial reduction in RWC was observed in the control treatment (T5; 33.33%), whereas KCl-treated plants (T6) maintained a higher RWC (50%), indicating the protective effect of KCl against water loss. In week 4, the RWC further improved in both treatments; however, KCl-treated plants (T8; 71.22%) showed a slightly higher RWC than the control ones (T7; 67.74%). Overall, KCl (100 ppm) influenced leaf water status in a time-dependent manner, with treated plants generally maintaining higher or comparable RWC than the controls, particularly during the later growth stages, indicating improved water retention capacity under KCl treatment. (See Figure 1c).

## Effect of potassium chloride on the vigor index of mungbean

The vigor index of mungbean seedlings was assessed after the application of potassium chloride (100 ppm) to evaluate seedling strength and overall growth performance under treated conditions. The results revealed clear differences between the control and KCl-treated plants across the different weeks. In week 1, the control treatment (T1) recorded a vigor index of 124, whereas KCl-treated seedlings (T2) exhibited a higher vigor index (180), indicating enhanced seedling vigor following KCl treatment. During week 2, the vigor index of the control plants (T3) was relatively low (81.11); however, KCl application (T4) resulted in a marked increase in the vigor index (161.78), suggesting improved early seedling growth under KCl application. In week 3, a similar trend was observed, where control plants (T5) showed a vigor index of 82.22, whereas KCl-treated plants (T6) exhibited a substantially higher vigor index (210), indicating a strong positive response to KCl treatment. In week 4, the vigor index further increased in both treatments; however, KCl-treated plants (T8) showed the highest vigor index (280) compared to the control (T7; 188). Overall, potassium chloride (100 ppm) consistently enhanced the vigor index of mungbean seedlings compared to their respective controls, indicating improved seedling robustness and growth performance under the respective treatment. (See Figure 1d).

### Different ratios

### Effect of potassium chloride on the root-shoot ratio of mungbean

The root-to-shoot ratio of mungbean seedlings was measured after the application of potassium chloride (100 ppm) to evaluate biomass allocation between below- and aboveground plant parts under given treated conditions. In week 1, the control treatment (T1) recorded a root–shoot ratio of 0.80, whereas KCl- treated plants (T2) showed a slightly higher ratio (0.82), indicating a marginal increase in root biomass allocation under KCl treatment. During week 2, the root-to-shoot ratio increased from 0.85 in the control (T3) to 0.89 in the KCl-treated plants (T4), suggesting enhanced root development relative to shoot growth under KCl treatment. In week 3, control plants (T5) exhibited a root–shoot ratio of 0.86, whereas KCl-treated plants (T6) showed a further increase (0.94), indicating a stronger shift towards root growth under given treated conditions. In week 4, the control treatment (T7) recorded a comparatively lower root–shoot ratio (0.78), whereas KCl-treated plants (T8) maintained a higher ratio (0.88). Overall, potassium chloride (100 ppm) generally increased the root–shoot ratio of mungbean across most weeks, suggesting an adaptive allocation of biomass towards root development under KCl applied conditions. (See Figure 1e).

### Effect of potassium chloride on the shoot weight ratio of mungbean

The shoot weight ratio of mungbean seedlings was recorded after the application of potassium chloride (100 ppm) to assess changes in shoot biomass allocation under KCl treated conditions. In week 1, the control treatment (T1) exhibited a shoot weight ratio of 0.75, whereas KCl-treated plants (T2) showed a slightly higher ratio (0.79), indicating a modest increase in shoot biomass under KCl treatment. During week 2, the shoot weight ratio increased from 0.80 in the control (T3) to 0.82 in KCl-treated plants (T4), suggesting improved shoot growth in response to potassium application. In week 3, the control plants (T5) recorded a shoot weight ratio of 0.90, whereas the KCl-treated plants (T6) showed a comparable value (0.90), indicating minimal difference between treatments at this stage. In week 4, shoot weight ratio further increased in both treatments; however, KCl-treated plants (T8) exhibited a slightly higher ratio (0.96) compared to the control (T7; 0.95). Overall, potassium chloride (100 ppm) maintained or slightly enhanced the shoot weight ratio of mungbean seedlings across all weeks, indicating a stable shoot biomass allocation under KCl stress conditions. (See Figure 1f).

### Effect of potassium chloride on the root weight ratio of mungbean

The root weight ratio of mung bean seedlings was recorded after the application of potassium chloride (100 ppm) to assess changes in root biomass allocation under stress conditions. In week 1, the control treatment (T1) exhibited a root weight ratio of 0.60, whereas KCl-treated plants (T2) showed a slightly higher ratio (0.64), indicating an early enhancement in root biomass following KCl treatment. During week 2, the root weight ratio increased from 0.68 in the control (T3) to 0.73 in the KCl-treated plants (T4), suggesting improved root growth in response to potassium application. In week 3, the control plants (T5) recorded a root weight ratio of 0.77, whereas the KCl-treated plants (T6) showed a higher value (0.85), indicating a significant positive effect of KCl on root biomass allocation at this stage. In week 4, the root weight ratio slightly decreased in the control plants (T7; 0.74) but remained high in KCl-treated seedlings (T8; 0.84), demonstrating that potassium chloride consistently promoted root development across the experimental period. Overall, potassium chloride (100 ppm) enhanced root biomass allocation in mungbean seedlings, reflecting improved root growth and potential nutrient uptake following KCl treatment. (See Figure 2a).

### Effect of potassium chloride on stress tolerance index

### Effect of potassium chloride on Plant Height Stress Tolerance Index of mungbean

The plant height stress tolerance index (PHSI) of mungbean seedlings was recorded following the application of potassium chloride (100 ppm) to assess the ability of the plants to maintain growth under KCl treatment conditions. In Week 1, the KCl-treated plants (T2) exhibited a remarkably high PHSI of 131.58, indicating a strong early-stage growth response and high tolerance facilitated by potassium application. In Week 2, the PHSI was recorded at 121.79 (T4), suggesting that while the index adjusted, the seedlings maintained a robust growth advantage under the 100 ppm KCl treatment. By Week 3, the KCl- treated plants (T6) exhibited a PHSI of 116.49, continuing to demonstrate effective stress mitigation and sustained vertical development. In the final assessment during Week 4, the PHSI of the KCl-treated seedlings (T8) reached 119.44, reflecting a consistent and stable tolerance level throughout the experimental period. Overall, the application of potassium chloride (100 ppm) consistently enhanced the plant height stress tolerance index across all four weeks, demonstrating that KCl treatment effectively supports the stability and resilience of mung bean growth against environmental stress. (See Figure 2b).

### Effect of potassium chloride on root length stress tolerance index of mungbean

The Root Length Stress Tolerance Index (RLSI) of mung bean seedlings was recorded following the application of potassium chloride (100 ppm) to assess the efficacy of the treatment in promoting root elongation under mentioned treatment conditions. In Week 1, the KCl-treated plants (T2) exhibited an RLSI of 114.81, indicating an immediate positive response in primary root development following potassium application. During Week 2, the RLSI increased to 123.33 (T4), suggesting that the seedlings continued to enhance their subterranean growth and osmotic adjustment capabilities in response to KCl treatment. By Week 3, the KCl-treated plants (T6) reached their peak RLSI of 150.00, representing a significant surge in root growth resilience. This high index suggests that by the third week, the potassium application reached its maximum efficacy in mitigating growth-retarding stress factors. In the final assessment during week 4, the RLSI was slightly adjusted to 140.00 (T8) but remained substantially higher than the initial levels, demonstrating a sustained and robust tolerance throughout the experimental period. Overall, the application of potassium chloride (100 ppm) consistently enhanced the root length stress tolerance index of mungbean seedlings. These data reflect a progressive improvement in root biomass allocation, highlighting the critical role of KCl in supporting root architecture and nutrient uptake efficiency under environmental stress. (See Figure 2c).

### Effect of potassium chloride on shoot fresh weight stress tolerance index of mungbean

The Shoot Fresh Weight Stress Tolerance Index (SFW-STI) of mungbean seedlings was recorded following the application of potassium chloride (100 ppm) to evaluate the capacity of the plants to maintain biomass under stress conditions. In Week 1, the KCl-treated seedlings (T2) exhibited a notably high SFW-STI of 130.43, indicating a strong initial enhancement in shoot fresh weight and improved stress tolerance facilitated by potassium application. During Week 2, the SFW-STI further increased to 134.48 (T4), indicating that potassium chloride continued to support shoot growth and effectively mitigated stress at this stage. By Week 3, a slight decline was observed, with the SFW-STI recorded at 118.92 (T6), suggesting some adjustment in biomass allocation but still maintaining a substantial advantage compared to typical stress responses. In Week 4, the SFW-STI remained relatively stable at 117.07 (T8), demonstrating consistent maintenance of shoot biomass under stress conditions throughout the experimental period. Overall, the application of potassium chloride (100 ppm) enhanced the stress tolerance of mung bean seedlings in terms of shoot fresh weight, indicating that KCl treatment effectively supports shoot growth stability and confers resilience under stress conditions. (See Figure 2d).

### Effect of potassium chloride on the root fresh weight stress tolerance index of mungbean

The Root Fresh Weight Stress Tolerance Index (RFW-STI) of mungbean seedlings was recorded to assess the effect of potassium chloride (100 ppm) on root biomass maintenance under stress conditions. In Week 1, the KCl-treated seedlings (T2) exhibited a high RFW-STI of 133.33, indicating a strong early-stage enhancement in root fresh weight due to potassium application. In Week 2, the RFW-STI further increased to 148.15 (T4), suggesting a pronounced positive impact of KCl on root growth, reflecting enhanced stress tolerance and improved root biomass accumulation. In Week 3, the RFW-STI decreased to 102.94 (T6), indicating a moderate reduction in root biomass allocation, although the seedlings still maintained root growth under stress conditions. By Week 4, the RFW-STI slightly recovered to 116.67 (T8), demonstrating that potassium chloride consistently supported root development and maintained biomass stability throughout the experimental period. Overall, the application of potassium chloride (100 ppm) enhanced the root fresh weight stress tolerance of Mungbean seedlings, reflecting improved root growth and resilience under environmental stresses. (See Figure 2e).

### Effect of potassium chloride on shoot dry weight stress tolerance index of mungbean

The Shoot Dry Weight Stress Tolerance Index (SDW-STI) of mungbean seedlings was measured to evaluate the effect of potassium chloride (100 ppm) on shoot biomass maintenance under stressed conditions. In Week 1, the KCl-treated seedlings (T2) exhibited a high SDW-STI of 146.67, indicating a strong early-stage improvement in shoot dry weight owing to potassium application. During Week 2, the SDW-STI slightly decreased to 135, suggesting a moderate reduction in shoot biomass accumulation, although the seedlings continued to maintain good growth under stress. In Week 3, the SDW-STI further declined to 125, reflecting a gradual reduction in shoot biomass allocation as stress persisted. By Week 4, the SDW-STI reached 119.44, demonstrating that while shoot growth under stress slightly diminished over time, potassium chloride consistently contributed to maintaining shoot biomass and supporting stress tolerance throughout the experimental period. Overall, the application of potassium chloride (100ppm) positively influenced shoot dry weight and enhanced the stress resilience of mungbean seedlings. (See Figure 2f).

### Effect of potassium chloride on Root Dry Weight Stress Tolerance Index of mungbean

The root dry weight stress tolerance index (RDW-STI) of mungbean seedlings was recorded to assess the impact of potassium chloride (100 ppm) on root biomass maintenance under stress conditions. In Week 1, the KCl-treated seedlings (T2) showed a high RDW-STI of 150, indicating a strong early-stage enhancement in root dry weight owing to potassium application. During Week 2, the RDW-STI slightly decreased to 141.18, reflecting a modest reduction in root dry weight, although the seedlings still maintained substantial root growth under stress. In Week 3, the RDW-STI further declined to 137.5, indicating a gradual decrease in root biomass allocation while sustaining moderate stress tolerance. By Week 4, the RDW-STI reached 135.71, demonstrating that potassium chloride consistently supported root dry weight accumulation and maintained biomass stability throughout the experimental period. Overall, the application of potassium chloride (100 ppm) positively influenced root dry weight, enhancing the stress tolerance and resilience of mungbean seedlings. (See Figure 3a).

### Mean relative growth rate of mungbean

The Mean Relative Growth Rate (RGR) of mungbean seedlings was calculated to assess the effect of potassium chloride (100 ppm) on overall growth dynamics during different developmental periods. Under control conditions, the RGR showed a gradual decline over time, with values of 0.0319 $g \cdot g^{-1} \cdot d^{-1}$ (Week 1–2), 0.0307 $g \cdot g^{-1} \cdot d^{-1}$ (Week 2–3), and 0.0291 $g \cdot g^{-1} \cdot d^{-1}$ (Week 3–4), reflecting the normal reduction in relative growth as the seedlings matured. In KCl-treated seedlings, the RGR was lower across all periods, with 0.0235 $g \cdot g^{-1} \cdot d^{-1}$ (Week 1–2), 0.0239 $g \cdot g^{-1} \cdot d^{-1}$ (Week 2–3), and 0.0204 $g \cdot g^{-1} \cdot d^{-1}$ (Week 3–4), indicating that potassium chloride at 100 ppm slightly reduced the relative growth rate compared to the control. Despite this reduction, KCl-treated seedlings maintained steady growth over time, suggesting that potassium application supported biomass accumulation and physiological stability under stress, although it moderated the rapid early-stage growth observed in the untreated seedlings. Overall, the application of potassium chloride influenced the growth pattern by sustaining growth under stress while slightly reducing the relative growth rate compared with the control. (See Figure 3b).

## Net assimilation rate of mung beans.

The Net Assimilation Rate (NAR) of mungbean seedlings was determined to evaluate the efficiency of photosynthetic accumulation per unit leaf area under potassium chloride (100 ppm) application. Under control conditions, NAR values gradually decreased over time, with 0.5289 $g \cdot cm^{-2} \cdot d^{-1}$ (Week 1–2), 0.2747 $g \cdot cm^{-2} \cdot d^{-1}$ (Week 2–3), and 0.1821 $g \cdot cm^{-2} \cdot d^{-1}$ (Week 3–4), reflecting the typical reduction in net photosynthetic efficiency as the seedlings matured and leaf area expanded. In KCl-treated seedlings, NAR was consistently lower than that in the control across all periods, with 0.3078 $g \cdot cm^{-2} \cdot d^{-1}$ (Week 1– 2), 0.1565 $g \cdot cm^{-2} \cdot d^{-1}$ (Week 2–3), and 0.0861 $g \cdot cm^{-2} \cdot d^{-1}$ (Week 3–4), indicating that potassium chloride reduced the photosynthetic rate per unit leaf area under stress conditions. Despite this reduction, KCl-treated seedlings maintained a steady NAR trend, suggesting that potassium application contributed to sustaining physiological activity and carbon assimilation under stress, even though the overall Efficiency per unit area was lower than that of unstressed controls. Overall, the application of potassium chloride influenced the net assimilation rate by moderating photosynthetic efficiency while supporting growth stability under stress. (See Figure 3c).

## Leaf area ratio of mung beans.

The Leaf Area Ratio (LAR) of mungbean seedlings was measured to assess the effect of potassium chloride (100 ppm) on leaf area development relative to total plant biomass. Under control conditions, LAR increased steadily over time, with values of 0.0603 $cm^2 \cdot g^{-1}$ (Weeks 1–2), 0.1119 $cm^2 \cdot g^{-1}$ (Weeks 2–3), and 0.1598 $cm^2 \cdot g^{-1}$ (Weeks 3–4), reflecting the gradual expansion of leaf area as the seedlings grew. In KCl-treated seedlings, LAR values were consistently higher than the control across all periods, with 0.0763 $cm^2 \cdot g^{-1}$ (Week 1–2), 0.1525 $cm^2 \cdot g^{-1}$ (Week 2–3), and 0.2375 $cm^2 \cdot g^{-1}$ (Week 3–4), indicating that potassium chloride promoted greater leaf area development relative to biomass under stress conditions. This enhancement in LAR suggests that KCl improved the photosynthetic surface per unit biomass, potentially supporting better light capture and carbon assimilation despite environmental. Stress. Overall, the application of potassium chloride positively influenced leaf area allocation in mungbean seedlings, contributing to improved growth and stress adaptation. (See Figure 3d).

## Morphology of mung bean plants:

Figure 17 depicts the morphological response of seedlings to KCl (100 mM) treatment across different time periods. Control plants showed typical development, with healthy branches and well-developed roots. In contrast, seedlings treated with KCl (100 mM) showed gradual growth suppression as exposure time increased. After one week of therapy, a modest reduction in shoot length and root growth was noticed. At two and three weeks, plants showed clear signs of stress, such as lower root extension and poorer stem development. By the fourth week, there was significant growth reduction and root damage compared to the control plants, demonstrating that sustained KCl stress had a major inhibitory influence on seedling morphology. (See Figure 4).

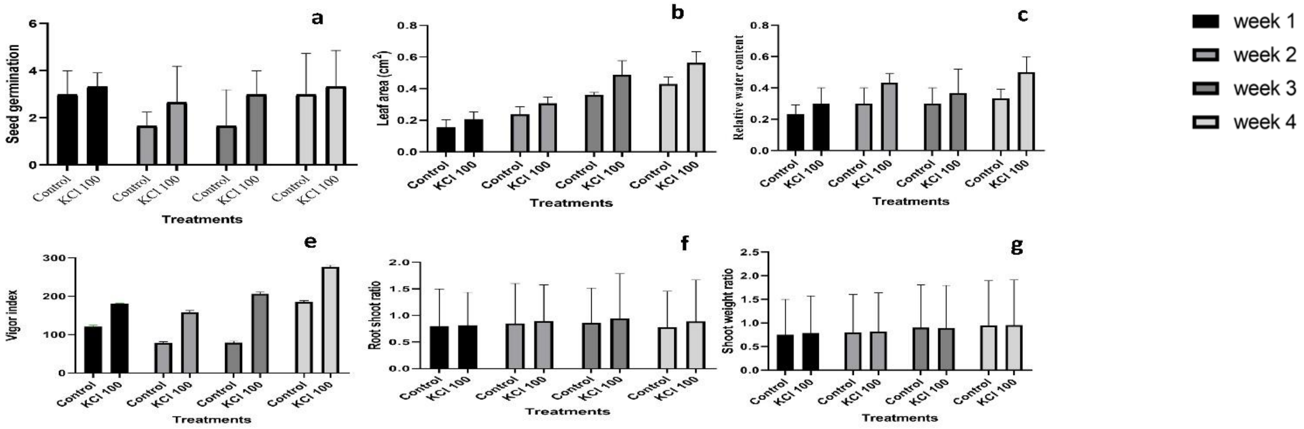

Figure 1: Represent the effect of potassium chloride on (a) seed germination data (b) leaf area (c) relative water content (d) vigor index (e) root shoot ratio (f) shoot weight ratio of mung bean grown under lab conditions. Data is calculated from 3 replicates with their respective error bars. Labels on the bars indicate significance among treatments ($p<0.05$).

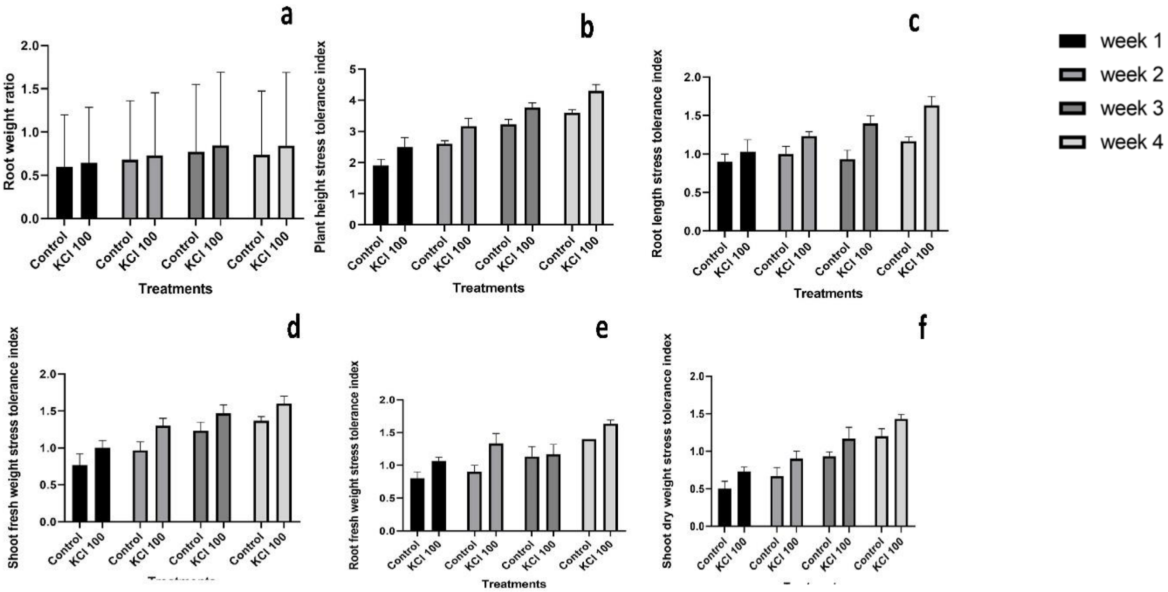

Figure 2: Represent the effect of potassium chloride on (a) root weight ratio (b) plant height stress tolerance index (c) root length stress tolerance index(d) shoot fresh weight stress tolerance index (e) root fresh weight stress tolerance index (f) shoot dry weight stress tolerance index of mung bean grown under lab conditions. Data is calculated from 3 replicates with their respective error bars. Labels on the bars indicate significance among treatments ($p<0.05$).

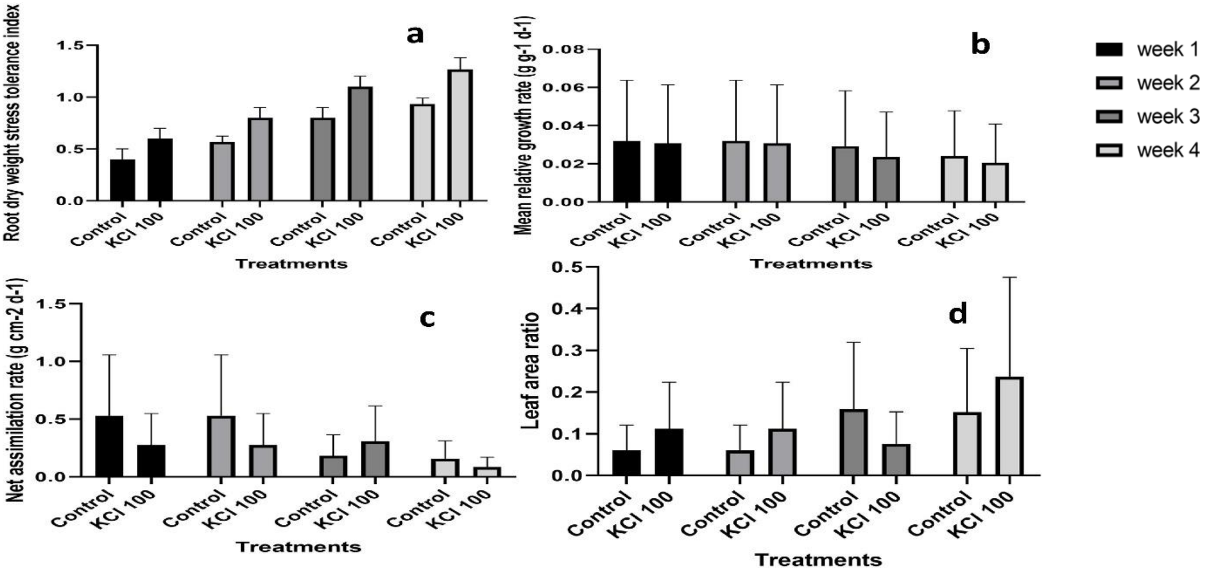

Figure 3: Represent the effect of potassium chloride on (a) root dry weight stress tolerance index (b) mean relative growth rate(c) net assimilation rate (d) Leaf area ratio of mung bean grown under lab conditions. Data is calculated from 3 replicates with their respective error bars. Labels on the bars indicate significance among treatments ($p<0.05$)

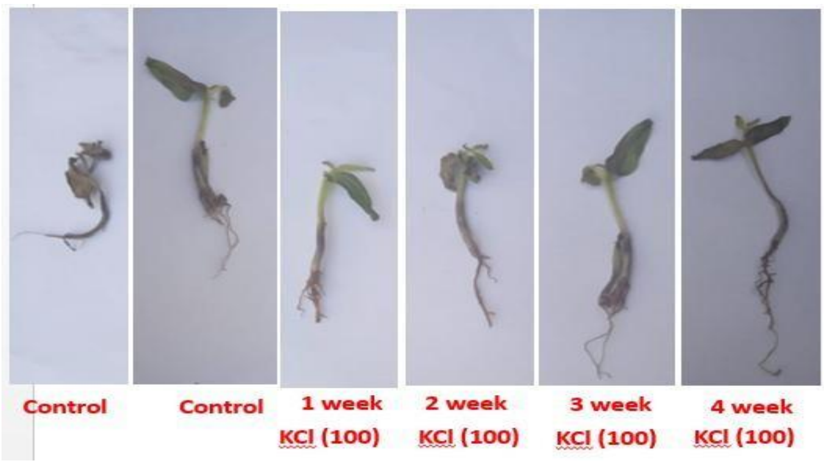

Figure 4: Mungbean seedlings treated with KCl (100 ppm) under lab conditions.

## DISCUSSION

The present investigation demonstrated that the application of potassium chloride (100 ppm) significantly modulated growth, physiological performance, and stress tolerance in mung bean (*Vigna radiata* L.) seedlings under environmental conditions. Potassium is a major macronutrient involved in enzyme activation, osmotic balance regulation, photosynthesis enhancement, and stress response mediation (Noor *et al*., 2025). The improvements observed in leaf area, vigor index, and relative water content (RWC) indicate that KCl played a protective role in maintaining plant functionality and growth stability under environmental conditions.

The role of K in maintaining cellular turgor, facilitating stomata movement, and supporting metabolic processes has been widely documented in legumes and other crops subjected to abiotic stress (Hasanuzzaman *et al*., 2018). Indeed, the enhanced leaf expansion in KCl-treated plants compared to controls in all four weeks suggests that potassium supported sustained leaf morphogenesis, even under suboptimal conditions.

The increase in leaf area ratio (LAR) observed with KCl treatment reinforces the view that potassium enhances the development of the photosynthetic surface area relative to plant biomass. The higher LAR in treated seedlings, especially evident from week 2 onwards, suggests an improved capacity for light interception, which could offset reductions in the net assimilation rate (NAR) observed under environmental condition. This pattern reflects a compensatory mechanism in which plants allocate resources to leaf expansion when photosynthetic efficiency per unit area is compromised, thereby optimizing the whole-plant carbon gain (Khan *et al*., 2025).

Previous studies have shown that K supplementation increases leaf area and overall growth performance under drought and salinity stress by stabilizing cell membranes and enhancing chlorophyll synthesis (Tufail *et al*., 2018). Therefore, the observed increases in LAR and leaf area in this study are consistent with enhanced stress resilience via improved canopy development. The RWC data further confirmed that KCl application improved the plant water status during stress exposure. Treated seedlings generally maintained higher or comparable RWC values than the controls across the experimental timeframe, particularly at later growth stages. Such improvements in water retention capacity can be attributed to the role of K in regulating osmotic adjustment and stomata aperture, which directly influence transpiration rates and water-use efficiency (Akhtar *et al*., 2023).

The maintenance of a higher RWC under stress indicates that KCl-treated plants were better able to preserve turgidity and cellular hydration, supporting continued metabolic function. Similar observations have been reported in other studies, where K nutrition mitigated the effects of water deficit by enhancing osmotic balance and improving stress tolerance indices (Li *et al*., 2013). Biomass allocation patterns, as reflected in the root–shoot ratio, shoot weight ratio, and root weight ratio, revealed adaptive shifts under KCl treatment. Treated plants showed higher root–shoot ratios at most sampling points, indicating a greater investment of resources in root development relative to shoot growth under stress.

This pattern aligns with the adaptive strategy of enhancing belowground growth to overcome water and nutrient limitations and is consistent with earlier findings in legumes and cereals under stress conditions when potassium was supplemented (Liu *et al*., 2021). Enhanced root biomass allocation likely contributes to improved water uptake and nutrient absorption, which are crucial for supporting aboveground growth under adverse conditions. The generally higher root weight ratios in KCl-treated seedlings support this interpretation and corroborate the hypothesis that potassium promotes root architecture that favors stress resilience (Liao *et al*., 2022). Stress tolerance indices (STIs) for plant height, root length, and biomass traits provided additional evidence that KCl enhanced the ability of mungbean seedlings to withstand stress. The consistently higher PHSI, RLSI, SFW- STI, RFW- STI, SDW- STI, and RDW- STI values in the treated plants across all weeks indicate that potassium chloride enabled the seedlings to maintain key growth parameters under stress. Elevated STIs have been linked to improved ion homeostasis and cell membrane stability under stress, both of which are strongly supported by potassium nutrition (Sardans *et al*., 2021). T

he particularly high RLSI in Weeks 2–4 suggests that root development, a critical determinant of stress adaptation, was substantially enhanced, enabling better exploration of soil resources even under challenging conditions. These results support the conclusion that KCl not only prevents severe stress damage but also actively promotes adaptive growth responses. Growth dynamics, including the relative growth rate (RGR) and assimilation parameters, provide important insights into how potassium modulates plant development under stress. Although RGR was lower in KCl-treated seedlings than in the control, this pattern likely reflects a trade-off between rapid biomass accumulation and the allocation of resources toward stress mitigation mechanisms. Such moderate growth responses are common under stress conditions, when plants prioritize survival and functional stability over rapid expansion (Abdullah *et al*., 2024). Future research should investigate the molecular mechanisms underlying these responses, including potassium transporter activity, stress signaling pathways, and gene expression changes in response to KCl treatment.

## CONCLUSION

The present study concluded that potassium chloride (100 ppm) plays a significant role in modulating the growth performance of mungbean (*Vigna radiata* L.) seedlings under environmental condition. The application of KCl markedly improved plant growth indices for shoot and root dry weights, indicating enhanced biomass stability and adaptive capacity throughout the experiment. Overall, potassium chloride application emerged as an effective strategy for improving stress tolerance and growth sustainability in mungbeans, highlighting its potential role in nutrient-based stress management practices for legume crops.

### Author Contributions

Abdullah conceived and designed the experiment, conducted the research, performed data analysis, and wrote the original draft of the manuscript. The author also reviewed and approved the final version of the manuscript.

### Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

### Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### Conflict of Interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

### Acknowledgements

The author is grateful to the National Institute for Genomics and Advanced Biotechnology, National Agricultural Research Centre (NARC), Islamabad, Pakistan, for providing laboratory facilities and technical support to conduct this study.

### Ethics Statement

This study did not involve human participants or animals. All experimental procedures were conducted in accordance with institutional guidelines for plant research.

## REFERENCES:

Abdullah, H. A., and I. Ullah. 2024. Bioinoculation of rhizospheric and bulk soil fungi enhance growth, quality, and resilience of maize seedlings. *SABRAO J. Breed. Genet*, 56(6): 2416-2429

Abdullah, S. A., M. A. Zia, M. A., Khan, I. U., Khan, A., Maab, H., Zaib, S., ... and Haq, N. U. 2025. Genotype-specific influence of exogenous silicon on wheat under NaCL-induced salinity: A pot experiment. *Pakistan Journal of Weed Science Research*,31(4): 217-227.

Akhtar, M. N., M. W. Akhtar, A. A. Rahi, and T. ul Haq. 2023. Enhancing water use efficiency by using potassium-efficient cotton cultivars based on morphological and biochemical characteristic. In *Best Crop Management and Processing Practices for Sustainable Cotton Production*. IntechOpen.

Du, M., J. Xie, B. Gong, X. Xu, W. Tang, X. Li, and M. Xie. 2018. Extraction, physicochemical characteristics and functional properties of Mung bean protein. *Food Hydrocolloids*, 76: 131-140

Ganesan, K., and B. Xu. 2018. A critical review on phytochemical profile and health promoting effects of mung bean (*Vigna radiata*). *Food Science and Human Wellness*, 7(1): 11-33.

Hasanuzzaman, M., M. B. Bhuyan, K. Nahar, M. S. Hossain, J. A. Mahmud, M. S. Hossen, and M. Fujita. 2018. Potassium: a vital regulator of plant responses and tolerance to abiotic stresses. *Agronomy*, 8(3): 31.

Hou, D., L. Yousaf, Y. Xue, J. Hu, J. Wu, X. Hu, and Q. Shen. 2019. Mung bean (*Vigna radiata* L.): Bioactive polyphenols, polysaccharides, peptides, and health benefits. *Nutrients*, 11(6): 1238.

Khan, J., S. Aziz, S. Ali, T. Noor, S. Shoukat, S. Zaib, and M. A. Zia. 2025. Endophytic fungi from Oxalis stricta enhance growth, secondary metabolite production, and photosynthetic efficiency in maize (*Zea mays* L.). *Journal of Pure and Applied Agriculture*, 10(1).

Li, Y., H. Li, Y. Li, and S. Zhang. 2017. Improving water-use efficiency by decreasing stomatal conductance and transpiration rate to maintain higher ear photosynthetic rate in drought-resistant wheat. *The Crop Journal*, 5(3): 231-239.

Liao, Q., S. Gu, S. Kang, T. Du, L. Tong, J. D. Wood, and R. Ding. 2022. Mild water and salt stress improve water use efficiency by decreasing stomatal conductance via osmotic adjustment in field maize. *Science of the Total Environment*, 805: 150364

Liu, J., T. Hu, P. Feng, D. Yao, F. Gao, and X. Hong. 2021. Effect of potassium fertilization during fruit development on tomato quality, potassium uptake, water and potassium use efficiency under deficit irrigation regime. *Agricultural Water Management*, 250: 106831.

Mandal, M., R. S. Lodhi, S. Chourasia, S. Das, and P. Das. 2025. A review on sustainable slow-release N, P, K fertilizer hydrogels for smart agriculture. *ChemPlusChem*, 90(3): e202400643.

Mikkelsen, R. L., and T. L. Roberts. 2021. Inputs: potassium sources for agricultural systems. *Improving Potassium Recommendations for Agricultural Crops*, 47-74.

Mohan, N. G., P. Abhirami, and N. Venkatachalapathy. 2020. Mung bean. In *Pulses: Processing and Product Development* (pp. 213-228). Cham: Springer International Publishing.

Ngomat, M. S. 2019. The Effects of Potassium Chloride Application Rates of Potato Growth, Weight and Yield in Saboti Sub County Kenya (Doctoral dissertation, KeMU).

Noor, I. A., I. Ullah, I. Ahmed, and H. U. Rahman. 2025. Isolation and characterization of plant growth promoting fungi from the rhizosphere and bulk soil of *Abelmouschus esculentus* L. *Sarhad Journal of Agriculture*, 41(1).

Prakash, S., and J. P. VermaP. 2016. Global perspective of potash for fertilizer production. In *Potassium solubilizing microorganisms for sustainable agriculture* (pp. 327-331). New Delhi: Springer India.

Sabah, N. U., A. T. Mukkram, M. Z. Manzoor, A. Elgharably, S. Shoukat, T. I. Abdullah, and I. Ullah. 2026. Organic amendments improve rock phosphate solubilization and promote maize growth under alkaline soil conditions. *Pak. J. Bot*, 58: 6.

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

Tufail, A., H. Li, A. Naeem, and T. X. Li. 2018. Leaf cell membrane stability-based mechanisms of zinc nutrition in mitigating salinity stress in rice. *Plant biology*, 20(2): 338-345.

Viju, M. A. U. 2024. Evaluation of potassium requirement through polyhalite multinutrient fertilizer for enhancement of quality and yield of bt. Cotton under different irrigation levels in inceptisol (doctoral dissertation, mahatma phule krishi vidyapeeth).

Wanyama, J., S. Kiraga, E. Bwambale, and A. Katimbo. 2023. Improving nutrient use efficiency through fertigation supported by machine learning and internet of things in a context of developing countries: Lessons for Sub-Saharan Africa. *Journal of Biosystems Engineering*, 48(4): 375-391.

Yi-Shen, Z., S. Shuai, and R. FitzGerald. 2018. Mung bean proteins and peptides: Nutritional, functional and bioactive properties. *Food and Nutrition Research*, 62: 10-29219.

Zia, M. A., S. Shoukat, S. Aziz, I. U. Khan, A. Khan, H. Maab, and S. Zaib. 2025. Co-expression of ZmVPP1, ZmNAC111, and ZmTIP1 confers enhanced drought tolerance in maize (*Zea mays*). *Journal of Plant Production and Sustainability*, 1(1).