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Original Research

Effect of Foliar Application of Zinc on Growth, Yield, and Quality of Mung Bean (*Vigna radiata* L.) under Different Irrigation Regimes

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Abstract

Zinc (Zn) is an essential micronutrient that enhances crop resistance under water-deficient conditions by regulating plant physiological mechanisms and improving the accumulation of compatible solutes, which help maintain higher turgor potential and plant water retention in response to drought. A field experiment was conducted to ascertain an optimum combination of foliar-applied Zn and irrigation for boosting the growth and yield of mung bean. The experiment was comprised of two factors i) irrigation viz. no irrigation (I_0), irrigation at flowering stage (I_1), irrigation at pod initiation stage (I_2) and irrigation at flowering and pod initiation stages (I_3) and ii) Zn foliar application viz. no Zn (Zn_0), 0.3% at flowering stage (Zn_1), 0.3% at pod initiation stage (Zn_2) and 0.3% at flowering and pod initiation stages (Zn_3). Irrigation at the flowering and pod initiation stage combined with a foliar spray of 0.3% zinc solution produced the tallest plants (57.95 cm), maximum biological yield (4842.5 kg ha^{-1}), seed yield (1434.5 kg ha^{-1}), root weight (4.48 g plant^{-1}), root-to-shoot ratio (0.09), seed protein (25.24%), and zinc content (46.03 mg kg^{-1}). These values were recorded under this treatment. However, the lowest value for these parameters was recorded from plants that were grown without irrigation and Zn application. The maximum root length (33.04 cm) was recorded when 0.3% Zn was applied at flowering and pod initiation stages under no irrigation. This research provides evidence that under no irrigation conditions, Zn application at 0.3% at the flowering stage can mitigate drought stress, as reflected by greater proliferation of mung bean. The results further revealed that foliar application of 0.3% Zinc at

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flowering and pod initiation stage, accompanied by irrigation at these stages, is effective in improving mung bean growth, seed yield, and Zn contents under semi-arid agro-ecological conditions of Pakistan.

Keywords: drought stress, growth, irrigation, mung bean, yield, zinc

Introduction

Globally, pulses are an important source of vegetable proteins, vitamins, and micronutrients [1]. Worldwide, mung bean is grown on an area of 6 million hectares, with average yields of 0.73 t/ha [2]. The top mung bean-producing countries are India, China, Myanmar, and Thailand. The major pulses grown and consumed in Pakistan are chickpea (*Cicer arietinum* L.), mung bean (*Vigna radiata* L.), lentil (*Lens culinaris* L.), and black gram (*Vigna mungo* L.). Among these pulses, mung bean is the most important summer pulse crop of Pakistan, and it occupies 18% of the total area under pulses, contributing 16% to the total pulses production [3]. It is cultivated on 302,000 hectares of land with 264,000 tons of production [4]. It is cultivated mostly at high temperatures (27-30°C) under rain-fed conditions with low humidity [5] throughout the world, including Pakistan. Due to erratic rainfall, the crop faces water stress at different growth stages and consequently its growth and yield are seriously reduced. Water deficiency diminishes crop yield by reducing water absorption, gas exchange rates, and leaf water potential [6]. Water-deficient environments reduce stomatal functioning, and consequently, leaf temperature becomes supraoptimal, which leads to crop wilting [7]. The drought stress conditions also decrease cell membrane permeability, chlorophyll synthesis, and nutrient absorption; therefore, the photosynthetic efficiency of plants is adversely affected [8]. Thus, drought stress becomes the most crucial constraint in realizing the full yield potential of the mung bean crop [5].

However, in the present situation of water scarcity for agriculture around the globe [9], there is a dire need to identify the most critical growth stages of mung bean for irrigation so that maximum yield can be harvested with minimum water input. In addition to this, other agronomic approaches can also be integrated to cope with this situation. The application of mineral nutrients is recognized as the most efficient method to mitigate the harmful effects of drought. Among micronutrients, the importance of Zn in plant growth and development under water scarcity is well documented [10]. Under water stress conditions, Zn supply to plants regulates osmolytes accumulation, plant water relations, cell membrane integrity, stomatal conductance, and improves photosynthesis and water use efficiency, thus causing significant improvement in plant growth and yield [11, 12]. Additionally, Zn counteracts the negative consequences of drought stress by enhancing the concentration of stress proteins, interacting with plant hormones, and stimulating antioxidant enzymes. Zinc availability increases drought-stress tolerance of a crop by improving the synthesis of glycine-betaine [13] and amino acids because these are recognized for their regulatory role in osmotic homeostasis in a stress environment [14].

Despite the crucial role of Zn in drought stress alleviation in different crops, its deficiency has been reported in 70% of agricultural soil in Pakistan. Zn-depleted soils not only reduce crop final produce, but they also result in poor quality of grain and forage crops, leading to hidden hunger in humans [15, 16]. Different approaches, such as supplementation and industrial food fortification, may be beneficial in eliminating micronutrient deficiencies in staple foods. A new approach, bio-fortification, that depends on plant breeding, modern biotechnology, and agronomic management strategies, including mineral fertilization to enhance the micronutrient contents of food crops, has the potential to improve the nutritional quality and health of people living in urban and rural areas of developing countries.

Drought stress negatively affects several aspects of legume growth and development by disturbing turgor pressure, cell expansion, stomatal closure, photosynthesis, and causing oxidative stress, membrane damage, and hormonal shifts [16, 17]. Therefore, it is necessary to check whether foliar application of zinc enhances the growth, yield, and quality of mung bean (*Vigna radiata* L.) by improving physiological mechanisms. Whether Zn's beneficial impacts are more pronounced under water-deficient conditions remains unclear. Keeping in view the above-mentioned facts, the present research work was planned with the following objectives: 1) to improve the growth and yield of mung bean by foliar application of Zn under water deficit conditions, 2) to evaluate the effect of deficit irrigation and foliar Zn level on seed quality of mung bean.

Materials and Methods

Experimental Site

A field experiment was conducted at the Agronomic Research Area, College of Agriculture, University of Sargodha, during the spring season of 2020. Soil analysis was performed prior to crop seeding. The soil samples were collected using a soil auger to a depth of 15 cm. The soil was sandy clay loam and had a good drainage capacity. Various physicochemical properties of soil, texture class, EC, pH, organic matter (%), N (%), available P (ppm), and available K (ppm), were

Table 1. Physicochemical analysis of air-dried soil of the experimental site.

Parameters	Values	Status
Texture class	---	Sandy Clay Loam
EC (1:2.5) dSm^{-1}	0.40	Non-Saline
pH	7.8	Medium alkaline
Organic matter (%)	0.84	Medium
N (%)	0.65	Medium
Available P (ppm)	17	Medium
Available K (ppm)	110	Medium
Available Zn (mg kg^{-1})	0.34	Deficient

determined by the procedure given in the ICARDA manual [18] and shown in Table 1.

Meteorological Data

The climatic conditions of the experimental site were subtropical. Total rainfall and maximum and minimum temperatures during the growth and development period of the mung bean in 2020 were obtained from the meteorological department and given in Table 2.

Experimental Designs and Treatments

The experiment consisted of two factors: irrigation and Zn foliar application. The research trial was carried out in a randomized complete block design with split-plot arrangement, irrigation in main plots, and Zn levels assigned to sub-plots with four replications. The size of the experimental unit was 3 m × 1.2 m. Irrigation levels were: No irrigation, Irrigation at flowering stage, Irrigation at pod initiation, Irrigation at flowering and pod initiation stages. Zn treatments were: No Zn, 0.3% Zn at flowering stage, 0.3% Zn at pod initiation, 0.3% Zn at flowering and pod initiation stages.

Crop Husbandry

The mung bean was planted on well-prepared soil with 2-3 cultivations followed by planking on March 25, 2020. Mung bean cultivar NM-2016 was planted. The seed was obtained from Punjab Seed Corporation. To obtain maximum germination, a 10 kg ha^{-1} seed rate was used. The crop was seeded in 30 cm apart rows using a manual drill. After germination, excess seedlings were thinned to maintain a 10 cm plant-to-plant spacing. The nitrogen, phosphorus, and potassium fertilizers were applied at 25:50:50 kg ha^{-1}, respectively. Foliar application of zinc at 0.3% and different irrigation levels were applied according to the treatment plan. $ZnSO_4$ was used as a source of Zn. For weed control, hoeing was done at different intervals. The mung bean crop was harvested manually at pod maturity, and plants were tied in bunches and hung in a shed until they were completely dried.

Observations Recorded

The data regarding growth, yield, and quality of the mung bean were recorded by using a standard protocol.

Growth and Yield Parameters

Five plants were randomly selected from each plot, and plant height (cm), number of pods per plant, pod length (cm), number of seeds per pod, and number of branches per plant of each plant were determined, and then the average of five plants was calculated. Biological yield was determined by harvesting the whole plot from each experimental unit and weighing using a field balance. Then the samples were dried in air, and the

Table 2. Meteorological data for the growing period of mung bean, 2020.

Month	T max °C	T min °C	R.F (mm)
Mar	25.50	17.63	88.40
Apr	39.13	26.75	17.82
May	43	32.38	39.35
June	38.88	30.30	4.80
Mean	35.13	24.61	-
Total Rain-fall	-	-	150.37

Table 3. Effect of irrigation and Zn levels on growth and yield attributes of mung bean.

Irrigation Level	Plant height (cm)	Branches plant^{-1}	Pods plant^{-1}	Pod length (cm)	Seeds pod^{-1}	100-seed weight (g)
I_0	45.74 B	10.12 C	14.69 D	10.34 D	9.88 D	4.33 D
I_1	52.56A	11.84 B	18.37 B	12.90 B	13.48 B	5.48 B
I_2	48.36 B	10.68 C	16.49 C	12.04 C	11.69 C	4.95 C
I_3	54.20 A	12.80 A	21.30 A	13.80 A	14.67 A	5.79 A
HSD	2.68	0.64	1.08	0.35	0.78	0.04
Zn Level						
Zn_0	47.86 C	11.02 B	16.82 C	11.81 B	11.06 B	4.99 D
Zn_1	50.73 B	11.44 AB	17.98 AB	12.49 A	12.62 A	5.19 B
Zn_2	49.60 B	11.15 AB	17.45 BC	12.09 B	12.85 A	5.08 C
Zn_3	52.66 A	11.82 A	18.60 A	12.69 A	13.19 A	5.29 A
HSD	1.61	0.71	1.05	0.32	0.60	0.06

pods were separated, and the seeds were weighed for seed yield determination. Yield per ha was determined by using collected data. After threshing, 100 seeds were randomly counted from each experimental unit with the help of a grain counter, and their weights were recorded using a weighing balance for the 100-seed weight. For root weight/plant, 5 plants from each treatment were uprooted after wetting the root zone, their roots were separated, and then the roots were washed and dried. After that, the average root weight/plant was calculated. Root length of the randomly selected five plants from each treatment was measured using a meter rod after they were uprooted. The average root length/plant was calculated. Root-to-shoot ratio was calculated by following the formula:

$$\text{Root to shoot ratio} = \frac{\text{Dry weight of roots}}{\text{Dry weight of top of the plant}}$$

Seed Quality Analysis

Seed Protein Contents (%)

For this, the Bremner, 1964 approach was used. The Kjeldahl method was used to calculate nitrogen in the seed. For this, 1 g of sample was placed in the Kjeldahl flask, followed by 5 mL of concentrated H_2SO_4 and a tablet for digestion. After mixing, the flask was placed on the digestion assembly for digestion until the mixture became transparent and the organic matter had been oxidized. After that, it was allowed to cool whilst being set to digest in a 100 mL volumetric flask, with the final volume being brought up to 100 mL by washing the digest and thoroughly mixing it. Then, 5 mL from the volumetric flask was transferred to the Markem Still Apparatus, and by twisting the funnel stopper, roughly 10 mL of NaOH (4% w/w) was slowly poured into the funnel. The funnel was then plugged, and a few milliliters of distilled water were added. Then, after roughly 5 min of distillation, the product was collected into a conical flask, which constituted nearly 5 mL of 2% boric acid. Drippings were collected for about one minute after around five minutes of this operation. Subsequently, the condenser was rinsed thoroughly, and the percentage of crude protein was calculated by utilizing the following formula.

$$\text{Crude protein (\%)} = \frac{(V_1 - V_2)\,N}{100\,W} \times 100 \times 6.25 \times 14$$

Where; V_1 = Titration of sample (ml), V_2 = Blank titration (ml), N = Standardized H_2SO_4 normality, W= 100 (weight of sample) (gm)

Seed Zinc Contents (mg/kg)

One gram of crushed grain sample was digested overnight in a 10 mL solution of HNO_3 and 70% $HClO_4$ (2:1 v/v) in Pyrex digestion flasks, then heated at 150°C on a hot plate until red fumes were no longer formed, and then the temperature was again raised to 250°C until samples were converted into clear material. These digested samples were then diluted to 25 mL with distilled water in a 50 mL volumetric flask, and after that, these digested samples were filtered. After that, using an atomic absorption spectrophotometer, the amount of grain Zn (mg kg^{-1}) was determined, as stated by Prasad et al. [19].

Statistical Analysis

Data collected on different growth, yield, and quality parameters were statistically analyzed by following Fisher's analysis of variance (ANOVA) technique.

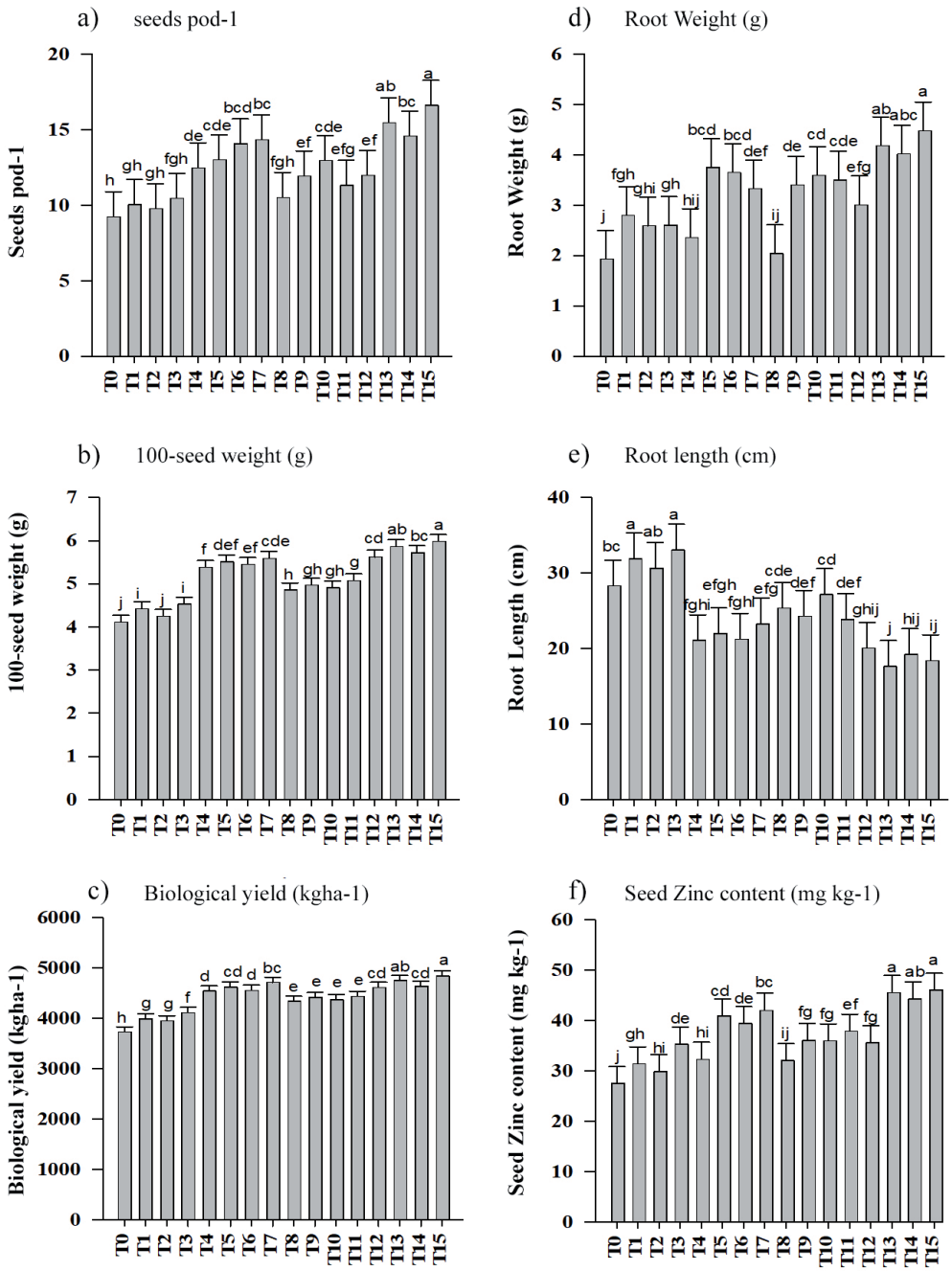

Fig. 1. Interactive effect of irrigation and Zn (T) on a) number of seeds per pod, b) 100 seed weight (g), c) biological yield (kg ha^{-1}), d) root weight (g), e) root length (cm) and f) seed Zinc contents (mg kg^{-1}) of mung bean seed. T_0: $I_0 \times Zn_0$,T_1: $I_0 \times Zn_1$,T_2: $I_0 \times Zn_2$,T_3: $I_0 \times$ Zn3,T_4: $I_1 \times Zn_0$,T_5: $I_1 \times Zn_1$,T_6: $I_1 \times Zn_2$,T_7: $I_1 \times Zn_3$,T_8: $I_2 \times Zn_0$,T_9: $I_2 \times Zn_1$,T_{10}: $I_2 \times Zn_2$,T_{11}: $I_2 \times Zn_3$,T_{12}: $I_3 \times Zn_0$,T_{13}: $I_3 \times Zn_1$,T_{14}: $I_3 \times Zn_2$,T_{15}: $I_3 \times Zn_3$.

Tukey's honestly significant difference (HSD) test was used to compare treatment with a 5% probability [20].

Results

Plant Height at Maturity

Mung bean plant height was significantly ($P \leq 0.05$) influenced by the foliar applications of Zn and irrigation levels; however, their interactive effect was non-significant (Table 3). Mung bean plants with maximum height (52.66 cm) were noted when 0.3% Zn was applied at the flowering and pod initiation stages. However, the minimum mung bean plant height (47.86 cm) was recorded when no foliar application of Zn was applied. The mung bean plants irrigated at the flowering and pod initiation stages produced maximum height (54.20 cm), and this was statistically similar to the mung bean plant height (52.56 cm) when irrigated at the flowering stage alone.

Number of Branches Plant^{-1}

The number of branches per plant of mung bean was significantly (P≤0.05) influenced by the foliar applications of Zn and irrigation levels (Table 3), while their interactive effect was found statistically non-significant. Mung bean plants irrigated at the flowering and pod initiation stages produced maximum branches per plant (12.80) and minimum (10.12) when no irrigation was applied. However, a statistically similar number of branches plant^{-1} was produced when irrigated at the flowering stage only. Mung bean also produced the maximum number of branches plant^{-1} (11.82) when 0.3% Zn was applied at flowering and pod initiation stages. The minimum number of branches per plant was recorded where no foliar application of Zn was applied.

Pods Numbers Plant^{-1}

Data in Table 3 showed a significant (P≤0.05) influence of foliar applications of Zn and irrigation levels on pods per plant of mung bean, while their interactive effect was found statistically non-significant. The maximum number of pods plant^{-1} (18.60) was observed where 0.3% Zn was applied both at flowering and pod initiation stages, and it was statistically at par with those where Zn was only applied at the flowering stage. However, the minimum number of pods plant^{-1} in mung bean was recorded when no foliar application of Zn was practiced. The application of irrigation at flowering and pod initiation stages produced maximum pods per plant (21.30), and it was statistically similar to (18.37) produced with irrigation at the flowering stage alone.

Pod Length (cm)

The data regarding the effect of foliar-applied Zn and irrigations on mung bean (*Vigna radiata* L.) pod length is presented in Table 3, and both significantly affect pod length, while their interactive effect showed non-significant results. Mung bean plants irrigated at the flowering and pod initiation stages produced maximum pod length (13.80 cm), and minimum pod length (10.34 cm) was observed where no irrigation was applied. Pod length was maximum (12.69 cm) when 0.3% Zn was applied at flowering and pod initiation stages, which was statistically at par with those where Zn was only applied at the flowering stage. However, the minimum (11.81 cm) mung bean pod length was recorded when no foliar application of Zn was done.

Number of Seeds Pod^{-1}

The effect of different Zn doses, irrigation levels (Table 3), and their interaction on seeds pod^{-1} of mung bean (Fig. 1) was statistically significant (P≤0.05). Irrigation at the flowering and pod initiation stage with foliar application of zinc at 0.3% at the flowering and pod initiation stage produced the maximum number of seeds per pod (16.62). However, statistically similar numbers of seeds per pod were produced by mung bean plants treated with 0.3% Zn at the flowering stage and irrigated at the flowering and pod initiation stages. The least number of seeds pod^{-1} were found in those plants that were grown without Zn and irrigation application.

100-Seed Weight (g)

Zn application levels, irrigation levels (Table 3), and their interaction on 100-seed weight (g) of mung bean were statistically significant (Fig. 1). Irrigation at the flowering and pod initiation stage with foliar application of zinc at 0.3% at the flowering and pod initiation stages produced seeds with the maximum 100-seed weight (5.98 g). However, statistically similar 100-seed weight was produced by mung bean plants treated with 0.3% Zn at the flowering stage and irrigated at the flowering and pod initiation stages. The minimum 100-seed weight (4.11 g) was found in those plants that were grown without Zn and irrigation application.

Biological Yield (kg ha^{-1})

The effect of different Zn levels, irrigation levels, and their interaction on the biological yield of mung bean (*Vigna radiata* L.) was statistically significant (Table 4, Fig. 1) (P≤0.05). Irrigation at flowering and pod Initiation stages with foliar application of Zinc at 0.3% at flowering and pod initiation stage produced maximum biological yield (4842.50 kg/ha) of the mung bean crop. However, statistically similar biological yield was produced by mung bean plants treated with 0.3% Zn at the flowering stage and irrigated at the flowering and pod initiation stages. Minimum biological yield (3729.50 kg/ha) was recorded where foliar application of Zn and irrigation were missed.

Seed Yield (kg ha^{-1})

Seed yield of mung bean was significantly influenced by the foliar applications of Zn and irrigation levels (Table 4), while their interactive effect was statistically non-significant. The maximum seed yield (1299.5 kg ha^{-1}) was observed where 0.3% Zn was applied both at flowering and pod initiation stages, and it was statistically at par with Zn applied at the flowering stage. However, minimum seed yield (1218.4 kg ha^{-1}) was recorded where mung bean plants were grown without foliar application of zinc. Mung bean plants irrigated at flowering and pod initiation stages produced maximum seed yield (1395.7 kg ha^{-1}), and the minimum (1093.8 kg ha^{-1}) was observed in the plots where no irrigation was applied.

Table 4. Effect of irrigation and Zn levels on yield, root-to-shoot characteristics, and quality of mung bean seed.

Irrigation Level	Biological yield (kg ha^{-1})	Seed yield (kg ha^{-1})	Root Weight per plant (g)	Root length (cm)	Root-to-shoot ratio	Seed Protein (%)	Seed Zinc content (mg kg^{-1})
I_0	3946.4 D	1093.8 D	2.48 C	30.96 A	0.06 C	21.44 D	30.98 C
I_1	4609.3 B	1353.3 B	3.27 B	21.87 C	0.07 AB	23.63 B	38.65 AB
I_2	4390.8 C	1193.6 C	3.13 B	25.16 B	0.07 BC	22.42 C	35.46 BC
I_3	4711.9 A	1395.7 A	3.92 A	18.82 D	0.08 A	24.86 A	42.84A
HSD	29.87	34.23	0.18	1.16	0.1	0.25	6.78
Zn Level							
Zn_0	4308.1 D	1218.4 D	2.33 B	23.69 ^{NS}	0.06 B	22.69 C	31.84 C
Zn_1	4444.7 B	1273.6 B	3.53 A	23.94	0.07 A	23.18 B	38.46 B
Zn_2	4378.9 C	1245.0 C	3.46 A	24.56	0.07 AB	22.90 C	37.35 B
Zn_3	4526.7 A	1299.5 A	3.48 A	24.62	0.08 A	23.58 A	40.29 A
HSD	37.72	21.51	0.21	-	0.01	0.26	1.24

Note: Zn_0: No Zn, Zn_1; 0.3% at flowering, Zn_2: 0.3% at pod initiation, Zn_3: 0.3% at flowering and pod initiation, I_0: No Irrigation, I_1: Irrigation at flowering stage, I_2: Irrigation at pod initiation, I_3: Irrigation at flowering and pod initiation.

Root Weight/Plant (g)

It is obvious from Table 4 that the effect of different Zn doses, irrigation levels, and their interaction (Fig. 1) on root weight/plant of mung bean (*Vigna radiata* L.) was statistically significant. Mung bean produced maximum root weight (4.48 g) when both Zn at 0.3% and irrigation were applied at the flowering and pod initiation stages. However, a statistically similar root weight/plant was produced with 0.3% Zn applied at the flowering stage and irrigated at the flowering and pod initiation stages. The minimum root weight (1.93 g) per plant was found in those plants that were grown without Zn and irrigation.

Root Length/Plant (cm)

Individual and interactive effects of foliar-applied Zn and different irrigation levels on mung bean (*Vigna radiata* L.) root length (cm) per plant are presented in Table 4 and Fig. 1. Root length per plant of mung bean was significantly influenced by the irrigation levels and the interactive effect of foliar-applied Zn and irrigation, whereas the effect of foliar-applied Zn was found statistically non-significant. The maximum root length (33.04 cm) per plant was observed in plots where 0.3% Zn was applied at flowering and pod initiation stages under no irrigation. However, the minimum root length (17.63 cm) per plant was recorded from those plots where mung bean plants were irrigated at both flowering and pod initiation stages with foliar application of Zn at the flowering stage only. Maximum root length (30.96 cm) per plant was observed in those plots where mung bean plants were grown without irrigation.

Root-to-Shoot Ratio

The data regarding individual and interactive effects of foliar-applied Zn and irrigations on mung bean (*Vigna radiata* L.) root-to-shoot ratio are presented in Table 4 and Fig. 1. Root-to-shoot ratio of mung bean was significantly influenced by the foliar applications of Zn and irrigation levels, while their interactive effect was found statistically non-significant. The maximum root-to-shoot ratio (0.084) was observed in plots where 0.3% Zn was applied both at flowering and pod initiation stages, and it was statistically at par with the root-to-shoot ratio of those plants where Zn was applied only at the flowering and pod initiation stages. However, a minimum root-to-shoot ratio (0.06) was recorded when no foliar application of Zn was applied. The application of irrigation at flowering and pod initiation stages produced the maximum root-to-shoot ratio (0.081). However, the minimum (0.06) root-to-shoot ratio of mung bean was recorded when no irrigation was applied.

Seed Quality Parameters

Seed Protein Content (%)

Protein content of mung bean seed was significantly ($P \leq 0.05$) influenced by the foliar applications of Zn and irrigation levels, while their interactive effect was found statistically non-significant. The maximum protein content (23.58%) was recorded when 0.3% Zn was applied at flowering and pod initiation stages. The minimum protein content (22.69%) was recorded where no foliar application of Zn was applied. The application of irrigation at flowering and pod initiation stages

produced the maximum protein content (24.86%) and the minimum (21.43%) when no irrigation was applied.

Seed Zn Content (mg kg^{-1})

The effect of different Zn doses, irrigation levels, and their interaction on Zn content of mung bean (*Vigna radiata* L.) was statistically significant ($P \leq 0.05$) (Table 4, Fig. 1). Irrigation at the flowering and pod initiation stage with foliar application of zinc at 0.3% at the flowering and pod initiation stage produced the maximum Zn content (46.03 mg kg^{-1}). However, statistically similar Zn content was recorded with 0.3% Zn at the flowering stage and irrigation at the flowering and pod initiation stages. The minimum Zn content was found where no application of Zn and irrigation was applied.

Discussion

Growth and Yield Contributing Traits

The improvement in yield-contributing traits is owing to the unique role of Zn in nitrogen metabolism. Zn increases chlorophyll content in leaves with concomitant improvement in growth and development in terms of plant height, number of branches, and number of pods. Increased source size and, as a result, improved partitioning of photosynthates towards meristematic tissues, i.e., new branches, explain the improvement in yield attributes. The increase in mung bean plant height with foliar application of Zn and irrigation at flowering and pod initiation stages is due to the critical role of Zn in auxin synthesis and to irrigation mitigating the adverse effects of water deficiency, which resulted in taller plants. These results are in agreement with Sultana et al. [21] who found that wheat plant height increased by foliar application of Zn at critical growth stages. Hussain et al. [22] also reported a significant improvement in mung bean growth with foliar application of Zn. The minimum plant height, where mung bean crop was grown without irrigation and Zn, might be due to the adverse effect of drought on photosynthesis, assimilate translocation, and carbon fixation, which resulted in stunted plants. Amanullah et al. [23] reported a significant decline in plant height under water deficit conditions. Naz et al. [24] also confirmed a significant increase in pea branches with the application of Zn. Ahmed et al. [25] also observed a significant increase in primary branches in tomato. The increase in the number of pods plant^{-1}, pod length, and seed number per pod with the application of Zn might be due to its crucial role in controlling auxin concentration in plants, which regulates many metabolic processes in the plant, and the role of Zn in development of stamens and pollens, while irrigation mitigates the adverse effects of water deficiency, which explains the improvement in pods per plant, pod length, and seeds per pod due to more dry matter accumulation with Zn application [26]. Zn aids plant growth and development by forming chlorophyll and nitrogenase, as well as promoting nodule formation and enzyme activation. It might be due to its enzymatic activity in the production of starch and the synthesis of proteins. Increased zinc availability to plants has boosted metabolic and enzymatic processes, resulting in an increase in the number of pods plant^{-1} of mung bean. The decrease in the number of pods plant^{-1} in plots receiving no irrigation was due to the fact that the production capacity of the plant decreases with water deficiency. Alipour et al. [27] also reported how mung bean cultivars respond to irrigation at different phonological phases and observed that irrigation timing had a substantial impact on yield and yield components. Rehman et al. [28] observed that the number of pods plant^{-1} was found to be lowest when no irrigation and zinc were applied, which could be because of drought. These results are in close conformity with those of Nadeem et al. [29], who found that drought stress might be the reason for less pod length due to a reduction in pod induction and young pod abortion. Unavailability of zinc and drought decrease the activity of the plant to carry out its normal functions. Hansel et al. [30] cited that the application of micro- and macronutrients mitigates the adverse effect of water deficiency in plants. A similar result was also reported by Borah et al. [31], who reported that the application of zinc had a significant impact on the number of seeds per pod. The decrease in the number of seeds per pod without the application of zinc and irrigation might be because of the fact that zinc deficiency leads to decreased content of auxin, and resultantly, many plant physiological processes are negatively influenced. Poudel et al. [32] found that the highest seed reduction in soybean was due to irrigation stress at the flowering stage.

Rabeh et al. [33] reported that foliar application of Zn resulted in a considerable increase in 1000-grain weight in rice. Our observations are endorsed by the findings of Ashikuzzaman et al. [34], who reported that soil application of $ZnSO_4$ substantially enhanced the wheat crop 1000-grain weight. The increase in mung bean biological yield with foliar application of Zn and irrigation at flowering and pod initiation stages was because the production of dry matter was influenced by Zn and irrigation application. These findings are similar to those of [9], who found that irrigation boosted dry matter production substantially. The decrease in final yield of mung bean due to no irrigation was probably due to the sensitivity of the crop to drought [35]. Saboor et al. [36] have also reported that the zinc application results in greater biological yield of maize. The rise in mung bean yield might be attributable to Zn's favorable effect on chlorophyll content, which aids in growth hormone production and influences photosynthesis and reproduction indirectly. It also aids in the production of enzymes and vitamins. This conclusion corroborated prior findings about the need for combining Zn applications to boost seed yield. Furthermore, Rehman

et al. [37] found that Zn had a considerable impact on yield in wheat. Islam et al. [38] also supported that Zn application on chickpea increased seed yield. These results are also in close conformity with those of Gupta et al. [39], who observed that foliar application of Zn improved grain yield of mung bean due to improvement in the number of grains pod^{-1} and grain size. Zinc application improves yield qualities during drought stress [40], which could explain why no irrigation and no zinc application resulted in a low yield. The interactive effect of zinc and irrigation was non-significant, and the reason might be that drought induces several factors in plants by affecting its physiological, growth, and developmental changes that ultimately affect the yield of a crop [41].

Root Components

An increase in root weight per plant of mung bean under foliar-applied zinc and irrigation produced plants with a healthy root system and even healthy secondary roots. Zn plays a pivotal role in cell differentiation and in metabolism, resulting in vigorous plant growth and a large root system, as well as improved growth characteristics in chili [42]. Similar results were also reported by a previous researcher [43], who reported that root growth is improved by the application of zinc under regular irrigation practices. The improvement in the root length per plant when Zn was applied at both flowering and pod initiation stages under no irrigation might be due to the fact that the plant's photoassimilates were directed more towards roots than the shoot to explore more soil volume. Protection against oxidative damage of the membrane is provided by micronutrients under drought conditions, and this might be the reason for the maximum root length per plant under no irrigation [44]. Drought affects several elements of growth and development, including root-to-shoot development, germination, photosynthesis, and reproductive stages, which may explain why the treatment with no irrigation had the lowest root-to-shoot ratio [29]. Under stress, a lower root-to-shoot ratio indicates stunted root growth, whereas a higher root-to-shoot ratio indicates root elongation relative to shoots to explore deeper soil profiles for absorption of water. The reason for the non-significant results for the interaction of zinc and irrigation might be due to the response of mung bean to water stress and zinc deficiency. Our results match with the findings of Lumactud et al. [45], where they found that due to water stress the root-to-shoot ratio is decreased.

Seed Quality Parameters

The foliar Zn spray enhanced the protein content of the mung bean seed. It was possibly due to increased zinc availability, which enhanced nitrogen uptake and absorption in plants. These findings are in accordance with Barla et al. [46], who documented that nutrient content in seed increases with the application of zinc. The highest protein contents in mung bean seeds with irrigation at flowering and pod initiation stages were due to the mitigation of water stress, and these observations are supported by the findings of [5], who claimed that protein content decreases as water stress increases. Zinc foliar application also resulted in a substantial rise in seed zinc content, and this is because of increased zinc absorption by the plant, which led to an increase in zinc content in the seed. Total absorption is a function of nutrient content in the seed and yield, resulting in a substantial rise in zinc uptake. These findings are similar to those of Tolay et al. [47], who reported that increasing Zn concentration to plants leads to higher uptake of nutrients by crops. Zinc also remobilizes effectively from leaves to grains. Our findings are also in accordance with those of [48], who documented that Zn application seemed a viable option to improve mung bean productivity along with higher grain Zn content. Similar results were also reported by Haider et al. [43], who reported that Zn foliar application was the most effective option for improving grain Zn concentration and grain yield. Kanwal et al. [49] reported that Zn nutrition prominently improved mung bean yield and Zn concentration in the grains.

Conclusions

The study showed the foliar application of 0.3% Zn at both flowering and pod stages combined with irrigation at these stages significantly improved growth, yield, and quality attributes of *Vigna radiata* L. While under limited water availability, a single irrigation at the flowering stage combined with Zn foliar application improved crop performance over no irrigation, Zn application promoted root biomass, and the root-to-shoot ratio led to good drought resilience. These findings suggest the integrated application of Zn with efficient irrigation scheduling to enhance the production and quality of mung bean under semi-arid conditions.

Limitations and Future Research Direction

The present study has several limitations. The research is conducted at a single location only; it cannot be applicable to varying agro-climatic conditions of the world. Only a single concentration of Zn is used, and results are based on yield and quality traits of mung bean only. In future, a multi-location trial can be conducted for more authenticity of results with different Zn levels and different methods of Zn application; moreover, a physiological study on Zn application under drought conditions can be conducted in further studies.

Conflict of Interest

The authors declare no conflict of interest.

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References

1. DREWNOWSKI A., CONRAD Z. Pulse crops: nutrient density, affordability, and environmental impact. Frontiers in Nutrition. **11**, 1438369, **2024**.
2. SEQUEROS T., OCHIENG J., SCHREINEMACHERS P., BINAGWA P.H., HUELGAS Z.M., HAPSARI R.T., SUEBPONGSANG P. Mung bean in Southeast Asia and East Africa: varieties, practices and constraints. Agriculture & Food Security. **10** (1), 1, **2021**.
3. PARC. Pakistan Agricultural Research Council, National Coordinated Pulses Program, National Agricultural Research Centre, Islamabad, Pakistan. **2021**.
4. Government of Pakistan, Economic Survey of Pakistan, Islamabad, Pakistan. 21-35, **2022**.
5. BANGAR P., CHAUDHURY A., TIWARI B., KUMAR S., KUMARI R., BHAT K.V. Morpho-physiological and biochemical response of mungbean (*Vigna radiata* L.) varieties at different developmental stages under drought stress. Turkish Journal of Biology. **43** (1), 58, **2019.**
6. FAROOQ M., GOGOI N., BARTHAKUR S., BAROOWA B., BHARADWAJ N., ALGHAMDI S.S., SIDDIQUE K.H.M. Drought stress in grain legumes during reproduction and grain filling. Journal of Agronomy and Crop Science. **203** (2), 81, **2017.**
7. SEHGAL A., SITA K., KUMAR J., KUMAR S., SINGH S., SIDDIQUE K.H., NAYYAR H. Effects of drought, heat and their interaction on the growth, yield and photosynthetic function of lentil (*Lens culinaris Medikus*) genotypes varying in heat and drought sensitivity. Frontiers in Plant Science. **8**, 1776, **2017**.
8. AWASTHI R., KAUSHAL N., VADEZ V., TURNER N.C., BERGER J., SIDDIQUE K.H., NAYYAR H. Individual and combined effects of transient drought and heat stress on carbon assimilation and seed filling in chickpea. Functional Plant Biology. **41**, 1148, **2014**.
9. ISLAM M.S., MOHSAN S., AFZAL S., AKMAL M.A., KHALID R. Phosphorus and sulfur application improve the chickpea productivity under rainfed conditions. International Journal of Agriculture and Biology. **13**, 713, **2011**.
10. UMAIR HASSAN M., AAMER M., UMER CHATTHA M., HAIYING T., SHAHZAD B., BARBANTI L., GUOQIN H. The critical role of zinc in plants facing the drought stress. Agriculture. **10** (9), 396, **2020**.
11. RASHEED A., LI H., TAHIR M.M., MAHMOOD A., NAWAZ M., SHAH A.N., ASLAM M.T., NEGM S., MOUSTAFA M., HASSAN M.U., WU Z. 2022. The role of nanoparticles in plant biochemical, physiological, and molecular responses under drought stress: A review. Frontiers in Plant Science. **13**, 976179, **2022**.
12. MA D., SUN D., WANG C., DING H., QIN H., HOU J., HUANG X., XIE Y., GUO T. Physiological responses and yield of wheat plants in zinc-mediated alleviation of drought stress. Frontiers in Plant Science. **8**, 860, **2017**.
13. MOVAHHEDI DEHNAVI M., YADAVI A., MERAJIPOOR M. Physiological responses of sesame (*Sesamum indicum* L.) to foliar application of boron and zinc under drought stress conditions. Journal of Plant Process and Function. **6** (20), 27, **2017**.
14. ZUSHI K. Comparison of chemical composition contents of tomato fruit grown under water and salinity stresses. Journal of Society of High Technology in Agriculture. **17**, 128, **2005**.
15. BAROOWA B., GOGOI N. Biochemical changes in black gram and green gram genotypes after imposition of drought stress. Journal of Food Legumes. **27** (4), 350, **2014**.
16. OGUZ M.C., AYCAN M., OGUZ E., POYRAZ I., YILDIZ M. Drought stress tolerance in plants: Interplay of molecular, biochemical and physiological responses in important development stages. Physiologia. **2**, 180, **2022**.
17. AHMAD H., LI J. Impact of water deficit on the development and senescence of tomato roots grown under various soil textures of Shaanxi, China. BMC Plant Biology. **21**, 241, **2021**.
18. ESTEFAN G., SOMMER J.R. Methods of soil, plant, and water analysis: A manual for the West Asia and North Africa region. ICARDA (International Center for Agricultural Research in the Dry Areas), 3rd Ed., Beirut, Lebanon. **2013**.
19. PRASAD P.V., BOOTE K.J., ALLEN L.H., SHEEHY J.E. Species, ecotype and cultivar differences in spikelet fertility and harvest index of rice in response to high temperature stress. Field Crops Research. **95**, 398, **2006**.
20. STEEL R.G.D., TORRIE J.H., DICKEY D.A. Principles and procedures of statistics: A biometric approach, (3rd Edition). McGraw Hill Book Co. Inc. New York. **1997**.
21. SULTANA N., IKEDA T., KASHEM M.A. Effect of foliar spray of nutrient solutions on photosynthesis, dry matter accumulation and yield in seawater-stressed rice. Environmental and Experimental Botany. **46** (2), 129, **2001**.
22. HUSSAIN M., SHAHID M.Z., MEHBOOB N., MINHAS W.A., AKRAM M. Zinc application improves growth, yield and grain zinc concentration of mung bean (*Vigna radiata* L.). Semina: Ciências Agrárias. **42** (2), 487, **2021a**.
23. AMANULLAH, YAR M., KHALID S., ELSHIKH M.S., AKRAM H.M., IMRAN, AL-TAWAHA A.R.M., AHMAD M., MUHAMMAD A., ULLAH S. Phenology, growth, productivity, and profitability of mungbean as affected by potassium and organic matter under water stress vs. no water stress conditions. Journal of Plant Nutrition. **45** (5), 629, **2022**.
24. NAZ S., LATIF M.U., HAIDER S.T.-A., ALI S., SARDAR H., AHMAD R., ANJUM M.A. Potential of foliar application of micronutrients on growth, yield, quality and nutraceutical properties of pea (*Pisum sativum* L.). Pakistan Journal of Botany. **54**, 931, **2022**.
25. AHMED R., UDDIN M.K., QUDDUS M.A., SAMAD M.Y.A., HOSSAIN M.M., HAQUE A.N.A. Impact of foliar application of zinc and zinc oxide nanoparticles on growth, yield, nutrient uptake and quality of tomato. Horticulturae. **9** (2), 162, **2023**.

26. SALEHI H., CHEHREGANI RAD A., SHARIFAN H., RAZA A., VARSHNEY R.K. Aerially applied zinc oxide nanoparticle affects reproductive components and seed quality in fully grown bean plants (*Phaseolus vulgaris* L.). Frontiers in Plant Science. **12**, 808141, **2022**.
27. ALIPOUR S., AMINI M.Z., HAIDARI M.D. Effects of regulated deficit irrigation on crop water productivity, yield components, and yield response factor of common bean (*Phaseolus vulgaris* L). Asian Journal of Water Research. **8**, 112, **2022**.
28. REHMAN H.U., RASOOL F., AWAN M.I., MAHMOOD A., WAKEEL A., HAJIBOLAND R. Irrigation and Zn fertilizer management improves Zn phyto-availability in various rice production systems. Journal of Plant Nutrition and Soil Science. **181** (3), 374, **2018**.
29. NADEEM M., LI J., YAHYA M., SHER A., MA C., WANG X., QIU L. Research progress and perspective on drought stress in legumes: a review. International Journal of Molecular Sciences. **20** (10), 2541, **2019**.
30. HANSEL F.D., AMADO T.J., RUIZ DIAZ, D.A., ROSSO L.H., NICOLOSO F.T., SCHORR M. Phosphorus fertilizer placement and tillage affect soybean root growth and drought tolerance. Agronomy Journal. **109** (6), 2936, **2017**.
31. BORAH L., SAIKIA J., BASUMATARY A. Effect of foliar application of zinc on growth and yield of garden pea (*Pisum sativum* L.) in Assam condition. International Journal of Chemical Studies. **9** (2), 869, **2021**.
32. POUDEL S., VENNAM R.R., SHRESTHA A., REDDY K.R., WIJEWARDANE N.K., REDDY K.N., BHEEMANAHALLI R. Resilience of soybean cultivars to drought stress during flowering and early-seed setting stages. Scientific Reports. **13** (1), 1277, **2023**.
33. RABEH H., EL-SALAM A., BADAWY S. Effect of zinc foliar application splits and rates integrated with humic acid on growth, yield, and grain quality of broadcast-seeded rice (*Oryza sativa* L.) in Northern Nile Delta Region, Egypt. Journal of Plant Production. **12** (5), 505, **2021**.
34. ASHIKUZZAMAN S.K.P., AHMED M.T., UPAMA S.A., UDDIN M.R., SARKER U.K. Soil applied zinc fertilizer enhanced yield and yield components of wheat. Journal of Agroforestry and Environment. **17** (1), 50, **2024**.
35. SIDDIQUI S.A., MAHMUD A., KHALIQ Q.A., HAQUE M.M., SOLAIMAN A., KARIM M.A. Growth and yield variations in mungbean varieties under water stress. Journal of Ecology. **5** (1), 37, **2023**.
36. SABOOR A., ALI M.A., HUSSAIN S., EL ENSHASY H.A., HUSSAIN S., AHMED N., GAFUR A., SAYYED R., FAHAD S., DANISH S. Zinc nutrition and arbuscular mycorrhizal symbiosis effects on maize (*Zea mays* L.) growth and productivity. Saudi Journal of Biological Sciences. **28** (11), 6339, **2021**.
37. REHMAN A., FAROOQ M., ULLAH A., NAWAZ A., UD DIN M.M., SHAHZAD B. Seed priming with zinc sulfate and zinc chloride affects physio-biochemical traits, grain yield and biofortification of bread wheat (*Triticum aestivum*). Crop and Pasture Science. **73** (5), 449, **2022**.
38. ISLAM M.R., KAMAL M.M., ALAM M.A., HOSSAIN J., SOUFAN W., SKALICKY M., BRESTIC M., HABIB-UR-RAHMAN M., EL SABAGH A., ISLAM M.S. Physiochemical changes of Mung bean [*Vigna radiata* (L.) R. wilczek] in responses to varying irrigation regimes. Horticulturae. **7** (12), 565, **2021**.
39. GUPTA S.P., SINGH P., VIVEK R., CHANDRA M.S., VERMA S.K., KUMAR A., MAURYA D.K., GUPTA S. Effect of micronutrients application on productivity and profitability of moong bean (*Vigna radiata* L.). Asian Journal of Soil Science and Plant Nutrition. **11**, 1660, **2022**.
40. SRIKANTH B., JAYALALITHA K., REKHA M.S. Zinc induced variations in dry matter production, partitioning and yield of mungbean (*Vigna radiata* L.) under water stress. Current Journal of Applied Science and Technology. **40** (8), 41, **2021**.
41. HUSSAIN M., FAROOQ S., HASAN W., UL-ALLAH S., TANVEER M., FAROOQ M., NAWAZ A. Drought stress in sunflower: Physiological effects and its management through breeding and agronomic alternatives. Agricultural Water Management. **201,** 152, **2018**.
42. AHMED M., ARA N., AMAN F., FAROOK A., ASGHAR, M., MUHAMMAD, N., AHMAD, Z., BIBI, R. Effect of iron and zinc on growth and yield of chili (*Capsicum Annuum* L.). Journal of Agriculture & Education Research. **2** (2), 1, **2024**.
43. HAIDER M.U., FAROOQ M., NAWAZ A., HUSSAIN M. Foliage applied zinc ensures better growth, yield and grain biofortification of mungbean. International Journal of Agriculture and Biology. **20** (12), 2817, **2018**.
44. ZAHEDI S.M., HARFI T., MARJANI M., VACULÍK M., AMINI M., SARIKHANI S., Various forms of foliar applied zinc improve drought acclimation in pomegranate: response of photosynthesis, osmoregulation and antioxidant defense. Journal of Soil Science and Plant Nutrition, **24** (2), 2694, **2024**.
45. LUMACTUD R.A., DOLLETE D., LIYANAGE D.K., SZCZYGLOWSKI K., HILL B., THILAKARATHNA M.S. The effect of drought stress on nodulation, plant growth, and nitrogen fixation in soybean during early plant growth. Journal of Agronomy and Crop Science. **209** (3), 345, **2023**.
46. BARLA S., SAHOO H., PATRA B. Effect of soil and foliar application of zinc and iron on yield, nutrient content and quality of summer mungbean. International Journal of Environment and Climate Change. **13** (9), 2099, **2023**.
47. TOLAY I. The impact of different Zinc (Zn) levels on growth and nutrient uptake of Basil (*Ocimum basilicum* L.) grown under salinity stress. PLoS One. **16** (2), e0246493, **2021**.
48. FAROOQ H., ISHTIAQ R., BABAR H., FARYAD M., AMEEN M., ABBAS M., MUSHTAQ Z., ALASMARI A., MONDOL M., ABDI G. Enhancing zinc and iron biofortification in mungbean (Vigna radiata L.) through various application method. Scientific Reports, **15** (1), **2025**.
49. KANWAL A., KHAN M.B., HUSSAIN M., NAEEM M., RIZWAN M.S., ZAFAR-UL-HYE M. Basal application of zinc to improve mung bean yield and Zinc-Grains Biofortfication. Phyton-International Journal of Experimental Botany. **89** (1), 87, **2020**.