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Effects of foliar zinc sulfate and silicon application on mung bean performance under flowering–pod set drought stress

Alham Mohamed Hassan[1*], Hanan Saed Abdaullh[2]
[1,2]Department of crop science, Faculty of Agriculture, Omar Al -Mukhtar University, Al Bayda, Libya.

تأثير الرش الورقي بكبريتات الزنك والسيليكون على أداء فول المنج تحت إجهاد الجفاف خلال التزهير والعقد

الهام محمد حسن[1*]، حنان سعد عبد الله[2]
[1،2]قسم المحاصيل، كلية الزراعة، جامعة عمر المختار، البيضاء، ليبيا

*Corresponding author: elham.hassan@omu.edu.ly

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Abstract:
This field study (summer season 2025) evaluated whether foliar zinc sulfate ($ZnSO_4$, 0.5%), silicon (magnesium silicate, 30 ppm), or their combined application could mitigate drought stress imposed during the flowering–pod set stage in mung bean by improving growth, leaf water status, and yield. Two irrigation regimes were applied: full irrigation (I1) and a drought window during flowering–pod set (I2). Foliar treatments included water spray (T0), $ZnSO_4$ (T1), silicon (T2), and $ZnSO_4$+silicon (T3). Under drought stress (I2), the combined spray (T3) produced the highest pod number (20.91 ± 0.58) compared with the control (11.78 ± 0.24), and increased seed yield from 1.00 ± 0.06 to 2.00 ± 0.02 t ha^{-1} (T0 vs T3). Likewise, seed yield per plant increased from 3.81 ± 0.03 to 5.61 ± 0.18 g $plant^{-1}$ under I2 (T0 vs T3). Foliar applications also improved leaf relative water content (RWC) under drought, increasing from 54.93 ± 1.65 in the control to 81.11 ± 0.80 with T3 (I2). Overall, foliar application of $ZnSO_4$+silicon was the most effective strategy for alleviating flowering–pod set drought effects on mung bean performance, particularly seed yield and leaf water status.

Keywords: Mung bean (Vigna radiata L.) Reproductive-stage drought stress; Foliar application; Zinc sulfate ($ZnSO_4$); Silicon (magnesium silicate).

الملخص:
هدفت هذه الدراسة الحقلية (الموسم الصيفي 2025) إلى تقييم كفاءة الرش الورقي بكبريتات الزنك ($ZnSO_4$) بتركيز 0.5%والسيليكون (مغنيسيوم-سيليكات بتركيز 30 جزءًا في المليون) وتداخلهما في التخفيف من أثر إجهاد الجفاف خلال مرحلتي التزهير والعقد في فول المنج، وذلك من خلال تحسين صفات النمو والوضع المائي للأوراق والمحصول. شملت الدراسة نظامي ري: ري كامل (I1) ونافذة جفاف خلال مرحلتي التزهير والعقد(I2) ، وأربع معاملات رش: ماء فقط (T0)، كبريتات الزنك(T1) ، السيليكون(T2) ، ومعاملة مشتركة زنك+سيليكون.(T3) تحت إجهاد الجفاف(I2) ، حققت معاملة الدمج (T3) أعلى عدد قرون (20.91 ± 0.58) مقارنة بالشاهد (11.78 ± 0.24)، ورفعت محصول البذور من 1.00 ± 0.06 إلى 2.00 ± 0.02 طن/هكتار (T0 مقابل .(T3 كما ارتفع محصول البذور للنبات من 3.81 ±

0.03 إلى 5.61 ± 0.18 غ/نبات تحت I2 (T0 مقابل T3). وحسّنت معاملات الرش الوضع المائي للأوراق تحت الجفاف، إذ ارتفع المحتوى المائي النسبي (RWC) من 54.93 ± 1.65 في الشاهد إلى 81.11 ± 0.80 عند معاملة الدمج (T3) ضمن I2. تشير النتائج إلى أن الرش الورقي المشترك بكبريتات الزنك والسيليكون يُعد خيارًا فعالًا للتقليل من آثار جفاف مرحلتي التزهير والعقد على أداء فول المنج، ولا سيما من حيث محصول البذور والوضع المائي للأوراق.

الكلمات المفتاحية: فول المنج(Vigna radiata L.) ، إجهاد الجفاف في مرحلة التزهير والعقد، الرش الورقي، كبريتات الزنك($ZnSO_4$) ، السيليكون (مغنيسيوم-سيليكات).

Introduction:

Mung bean (Vigna radiata L.) Wilczek] is a short-duration grain legume increasingly recognized for its contribution to diversified and sustainable cropping systems and for its production potential under warm environments [1]. Water scarcity is a defining global constraint for agriculture, and agriculture accounts for about 70% of freshwater withdrawals worldwide [2[. In Libya, water limitation is a structural production constraint; the AQUASTAT country profile reports total water withdrawal of about 5,830 million m³ in 2012, with ~83% used by agriculture and groundwater [including fossil groundwater] supplying over 95% of withdrawn water [3]. National-level FAO programming and situation information also frames water scarcity as a persistent constraint shaping agricultural development and livelihoods [4]. Moreover, FAO land-and-water documentation emphasizes Libya's extreme dryness and the importance of improved land and water management to sustain agricultural production under scarce water resources [5].

Drought stress reduces mung bean yield through combined impacts on plant water status, canopy development, and assimilate supply to reproductive sinks, with heightened sensitivity when water deficit coincides with flowering and early pod development [6]. Previous work has documented substantial morphophysiological and biochemical alterations in mung bean under drought stress, supporting the premise that maintaining functional plant water relations is central to protecting growth and yield formation [7]. Evidence from foliar-intervention studies further indicates that mung bean water relations and yield traits can respond to physiological modulation under foliar application regimes, with measurable changes in water-related and yield traits [8].

Field studies underline that stage-specific water supply is a key determinant of mung bean productivity and water productivity. Irrigation management in summer mung bean substantially influences growth indices and yield components and can improve water productivity, reinforcing that reproductive-phase water availability is critical for final yield [9]. This evidence supports targeting flowering–pod set drought as an agronomically meaningful stress window and assessing interventions that sustain plant hydration and canopy function to protect yield components.

Nutrient-based foliar strategies, particularly zinc [Zn], offer a practical route to support mung bean performance under field stress because Zn participates in key metabolic processes associated with growth and reproductive development [10]. Foliar Zn application has been associated with improved growth and productivity in mung bean under field conditions [11] From a grain quality and biofortification perspective, foliar micronutrient supplementation [including Zn] has been reported to enhance growth and yield-related performance and increase grain micronutrient concentration in mung bean [12].

Silicon [Si] has gained attention as a beneficial input under drought because evidence indicates that Si supplementation can improve physiological performance and drought-responsive traits, including leaf water status and, in many cases, yield stability across crops [13,14]. In mung bean, silicon-based interventions have been associated with improved drought-responsive morpho-anatomical and yield attributes under water deficit [16]. Zinc nutrition under water-limited conditions can also affect dry matter production and partitioning and yield responses in mung bea[17] , supporting the rationale for Zn-based management during drought windows [18]. More generally, foliar micronutrient programs under moisture stress have been explored as practical tools to stabilize growth and yield in mung bean and related field settings [19,20]. Accordingly, evaluating foliar zinc [$ZnSO_4$] and silicon [magnesium silicate], alone and in combination, under a defined flowering–pod set drought scenario is agronomically justified and directly relevant to water-limited production conditions in Libya [3, 5, 4, 2].

This field study aimed to quantify the extent to which foliar $ZnSO_4$ and foliar silicon, applied singly or in combination, mitigate flowering–pod set drought effects on mung bean [Vigna radiata [L.] Wilczek] performance by assessing growth, leaf water status [relative water content, RWC], yield components, seed yield, and selected seed quality traits under two irrigation regimes [full irrigation vs. drought imposed during flowering–pod set]. It was hypothesized that foliar $ZnSO_4$ and silicon—particularly when and sustaining growth, thereby enhancing yield components and final seed yield compared with untreated plants under drought.

Materials and Methods:

Experimental site:

Mung bean (Vigna radiata L.) Wilczek] is a short-duration grain legume increasingly recognized for its contribution to diversified and sustainable cropping systems and for its production potential under warm environments [1]. Water scarcity is a defining global constraint for agriculture, and agriculture accounts for about 70% of freshwater withdrawals worldwide [2[. In Libya, water limitation is a structural production constraint; the AQUASTAT country profile reports total water withdrawal of about 5,830 million m³ in 2012, with ~83% used by agriculture and groundwater [including fossil groundwater] supplying over 95% of withdrawn water [3]. National-level FAO programming and situation information also frames water scarcity as a persistent constraint shaping agricultural development and livelihoods [4[. Moreover, FAO land-and-water documentation emphasizes Libya's extreme dryness and the importance of improved land and water management to sustain agricultural production under scarce water resources [5].

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Results and discussion:

Deficit irrigation imposed during the critical flowering–pod set phase (30–40 DAS) significantly reduced plant height, branch number, leaf area, LAI, shoot and root dry weight, and ultimately yield-related traits across all treatments. These morphological and yield reductions under water stress are consistent with previous reports that drought during the reproductive stage strongly impairs relative water content (RWC), plant growth, and yield attributes in mung bean [6,13]. In contrast, foliar applications of $ZnSO_4$ (0.5%) and magnesium-silicate (30 ppm), either alone or in combination (T3), mitigated many of these negative effects, indicating that micronutrient supplementation during the stress window can partially compensate for water limitation.

Trait	Irrigation (F, P)	Treatment (F, P)	Irrigation× Treatment (F, P)
Plant height	143.4, P < 0.001	23.8, P < 0.001	0.21, P = 0.890
Branches	505.2, P < 0.001	358.8, P < 0.001	2.21, P = 0.120
Leaf area	524.8, P < 0.001	69.2, P < 0.001	0.55, P = 0.660
LAI	1820.0, P < 0.001	79.85, P < 0.001	0.25, P = 0.860
Shoot-dry weight	443.6, P < 0.001	59.2, P < 0.001	2.49, P = 0.090
RWC	131.4, P < 0.001	41.4, P < 0.001	9.10, P < 0.001
Root length	43.13, P = 0.007	37.89, P < 0.001	0.65, P = 0.590
Root-dry weight	358.7, P < 0.001	125.4, P < 0.001	3.43, P = 0.040
Root: shoot ratio	4.82, P = 0.120	0.44, P = 0.720	1.13, P = 0.360

Table (1): Growth, physiological and root traits -Anova (F, P)

Yield traits were also significantly affected by irrigation regime and foliar treatment, with strong irrigation and treatment main effects for pods per plant, seeds per pod, 100-seed weight, and seed yield, while germination showed no irrigation main effect and no irrigation × treatment interaction.

Table (2): Yield, yield components and germination-Anova (F, P)

Trait	Irrigation (F, P)	Treatment (F, P)	Irrigation × Treatment (F, P)
Pods	2618.0, P < 0.001	106.3, P < 0.001	3.20, P = 0.050
Seeds-per pod	160.1, P < 0.001	16.53, P < 0.001	0.49, P = 0.700
100-seed weight	485.6, P < 0.001	5.42, P = 0.008	3.27, P = 0.050
Seed-yield (g plant^{-1})	381.9, P < 0.001	108.8, P < 0.001	1.37, P = 0.290
Seed yield (t ha^{-1})	7774.0, P < 0.001	117.9, P < 0.001	8.85, P < 0.001
Germination	7.25, P = 0.070	5.31, P = 0.008	0.36, P = 0.780

For most growth and physiological traits (plant height, branches, leaf area, LAI, shoot and root dry weight), irrigation and treatment showed strong main effects, but the irrigation × treatment interaction was not statistically significant, whereas RWC and root dry weight showed significant irrigation × treatment interactions (Table 1). This implies that the ranking of treatments (T0 < T1 ≈ T2 < T3) was broadly consistent across full irrigation (FI; I1) and deficit irrigation (DI; I2) for many traits, even though absolute values were lower under DI, while interaction traits required interpretation within each irrigation regime (Table 3). Under deficit irrigation, T3 increased RWC by ~47.6% compared with the control (T0), whereas under full irrigation the increase was ~11.8%, supporting a stronger relative benefit under water limitation.

Table (3): Growth, physiology & root traits (mung bean) mean ± SE (n = 4)

Trait (unit)	I1_T0	I1_T1	I1_T2	I1_T3	I2_T0	I2_T1	I2_T2	I2_T3
Plant height (cm)	61.31 ± 0.45b	67.53 ± 2.46ab	71.58 ± 1.78a	73.62 ± 1.24a	45.69 ± 1.40c	50.05 ± 1.95bc	55.90 ± 1.67ab	58.56 ± 0.91a
Branches (no. plant^{-1})	3.96 ± 0.03c	4.97 ± 0.03b	5.04 ± 0.02b	6.22 ± 0.14a	3.00 ± 0.05c	4.01 ± 0.07b	3.95 ± 0.05b	4.97 ± 0.05a
Leaf area (cm^2)	32.02 ± 0.49c	35.94 ± 0.90b	38.73 ± 1.41b	43.35 ± 0.33a	20.00 ± 0.36c	24.18 ± 0.68b	27.75 ± 0.64a	30.39 ± 0.45a
LAI (–)	2.14 ± 0.04d	2.38 ± 0.02c	2.64 ± 0.04b	2.98 ± 0.05a	1.42 ± 0.07c	1.59 ± 0.05c	1.83 ± 0.05b	2.18 ± 0.05a
Shoot dry weight (g plant^{-1})	13.74 ± 0.43c	16.47 ± 0.58b	16.45 ± 0.43b	18.95 ± 0.28a	8.82 ± 0.26c	10.99 ± 0.26b	12.80 ± 0.27a	13.54 ± 0.32a
Root length (cm)	18.07 ± 0.26c	20.11 ± 0.31b	20.84 ± 0.37b	22.94 ± 0.50a	16.94 ± 0.51c	17.77 ± 0.72bc	19.40 ± 0.27b	21.31 ± 0.63a
Root:shoot ratio (–)	0.27 ± 0.04a	0.16 ± 0.01a	0.19 ± 0.06a	0.22 ± 0.06a	0.27 ± 0.09a	0.37 ± 0.04a	0.22 ± 0.08a	0.28 ± 0.04a
RWC (%)	84.50 ± 1.26b	87.49 ± 1.49ab	87.78 ± 2.90ab	94.47 ± 2.38a	54.93 ± 1.65c	63.56 ± 2.06b	69.98 ± 1.03b	81.11 ± 0.80a
Root dry weight (g plant^{-1})	3.39 ± 0.07d	3.73 ± 0.04c	3.97 ± 0.07b	4.20 ± 0.02a	2.67 ± 0.05c	2.83 ± 0.04c	3.10 ± 0.04b	3.54 ± 0.04a

Values are mean ± SE (n = 4). I1 and I2 denote irrigation regimes; T0–T3 denote fertilizer treatments (T0 = control). Within each irrigation regime, means followed by different letters are significantly different according to Tukey-adjusted multiple comparisons at α = 0.05; means sharing at least one letter (e.g., “ab”) are not significantly different.

Deficit irrigation also reduced yield components and seed yield (g plant^{-1} and t ha^{-1}) relative to FI, but foliar treatments improved these traits under both irrigation regimes, and T3 produced the highest or near-highest values for pods plant^{-1}, seeds pod^{-1}, 100-seed weight, and seed yield (Table 4). Seed yield (t ha^{-1}) showed a significant irrigation × treatment interaction, with T3 increasing seed yield by ~100% under DI compared with T0 and by ~34.8% under FI, indicating that the combined Zn + Si program was particularly effective at recovering drought-associated yield losses.

Table (4): Yield components & seed traits (mung bean) mean ± SE (n = 4)

Trait (unit)	I1_T0	I1_T1	I1_T2	I1_T3	I2_T0	I2_T1	I2_T2	I2_T3
Pods (no. plant^{-1})	19.97 ± 0.33d	21.66 ± 0.56c	23.39 ± 0.27b	26.41 ± 0.38a	11.78 ± 0.24d	15.01 ± 0.21c	17.20 ± 0.64b	20.91 ± 0.58a
Seeds per pod (no.)	11.41 ± 0.34b	12.45 ± 0.41ab	12.40 ± 0.13ab	12.96 ± 0.31a	8.53 ± 0.18b	9.61 ± 0.15a	9.96 ± 0.29a	10.57 ± 0.24a
100-seed weight (g)	5.32 ± 0.10a	5.20 ± 0.11a	5.50 ± 0.13a	5.39 ± 0.13a	4.72 ± 0.03b	4.88 ± 0.03b	4.95 ± 0.03b	5.38 ± 0.09a
Seed yield (g plant^{-1})	6.36 ± 0.09d	7.10 ± 0.14c	7.71 ± 0.17b	8.56 ± 0.13a	3.81 ± 0.03c	4.54 ± 0.07b	5.00 ± 0.13b	5.61 ± 0.18a
Seed yield (t ha^{-1})	1.84 ± 0.04b	1.99 ± 0.03b	2.42 ± 0.06a	2.48 ± 0.04a	1.00 ± 0.06d	1.26 ± 0.02c	1.48 ± 0.06b	2.00 ± 0.02a
Germination (%)	84.19 ± 2.49b	92.02 ± 1.79ab	92.52 ± 1.75ab	94.05 ± 2.18a	81.84 ± 2.93a	84.83 ± 1.63a	87.76 ± 2.78a	89.34 ± 1.97a

Values are mean ± SE (n = 4). Within each irrigation regime, means followed by different letters are significantly different (Tukey-adjusted, α = 0.05); means sharing at least one letter are not significantly different

Finally, germination percentage responded to foliar treatments, but neither the irrigation main effect nor the irrigation × treatment interaction was significant (Table 2). Related mung bean studies indicate that drought mitigation can coincide with improved photosynthetic pigment status and enhanced antioxidative defense, which is consistent with the improved plant water status observed here under foliar interventions (19). This stability, combined with the strong interaction-driven responses in RWC and seed yield under DI, suggests that Zn followed by Si during the flowering–pod set drought period improves final field performance without compromising seed quality (14).

Conclusion:

Deficit irrigation imposed during the critical flowering–pod set window (30–40 DAS) significantly reduced mung bean growth, plant water status, and yield performance, confirming the high sensitivity of this stage to water limitation. Your foliar treatments improved most traits under both irrigation regimes, with the combined program (T3: $ZnSO_4$ at 0.5% followed by silicon at 30 ppm) consistently delivering the highest or near-highest values. Importantly, the significant irrigation × treatment interactions for RWC, root dry weight, and seed yield (t ha^{-1}) indicate that the benefit of foliar Zn+Si was stronger under deficit irrigation, supporting its use as a mitigation strategy during reproductive drought.

Recommendations

- **Practical management:** In water-limited environments, apply a targeted foliar program during the reproductive drought risk period—$ZnSO_4$ (0.5%) and silicon (30 ppm) timed around flowering and early pod development, with a one-day interval between Zn and Si sprays (as in T3), to help maintain RWC and recover yield losses under deficit irrigation.
- **Irrigation scheduling:** Avoid irrigation withholding during 30–40 DAS whenever possible; if deficit irrigation is unavoidable, prioritize a timely recovery irrigation and maintain uniform post-stress irrigation to stabilize pod set and seed filling.
- **Reporting for Q1 journals:** For traits with significant I×T (RWC, root DW, seed yield t ha^{-1}), report and interpret treatment effects within each irrigation regime (simple effects), while traits without I×T should be discussed mainly as irrigation and treatment main effects.
- **Future research:** Validate the Zn+Si program across seasons and/or additional genotypes, and test dose/number of sprays to identify the most cost-effective schedule; adding mechanistic measurements (e.g., photosynthesis indicators, antioxidant activity, or water-use metrics) would strengthen the explanation of the observed mitigation effects.

References:

[1] MaxA Press. [2024]. Mungbean [Vigna radiata [L.] Wilczek] and its potential for crop production. Theoretical and Applied Agriculture. https://www.maxapress.com/article/id/67151029fa6c58164d6d4d47

[2] Food and Agriculture Organization of the United Nations [FAO]. [2023]. Water. FAO One Health. https://www.fao.org/one-health/areas-of-work/water/en

[3] Food and Agriculture Organization of the United Nations [FAO]. [2016]. AQUASTAT country profile – Libya. Rome, Italy: FAO. https://openknowledge.fao.org/server/api/core/bitstreams/4a130983-22a9-497c-b5ac-562dce64e236/content

[4] Food and Agriculture Organization of the United Nations [FAO]. [2022, February 16]. Libya. Building Forward Better initiative. https://www.fao.org/in-action/building-forward-better/countries/libya/en

[5] Food and Agriculture Organization of the United Nations [FAO]. [n.d.]. Land and water management in Libya. FAO Knowledge Repository. https://openknowledge.fao.org/server/api/core/bitstreams/514cfed5-e1f9-4ba4-a5a5-254ba157eeb0/content

[6] Bangar, P., Chaudhury, A., Tiwari, B., Kumar, S., Kumari, R., & Bhat, K. V. [2019]. Morphophysiological and biochemical response of mungbean [Vigna radiata L.] genotypes to drought stress. PubMed Central. https://pmc.ncbi.nlm.nih.gov/articles/PMC6426646/

[7] Islam, M. R., et al. [2023]. Water relations and yield characteristics of mungbean as influenced by foliar application of gibberellic acid [GA_3]. Frontiers in Ecology and Evolution, 11, 1048768. https://doi.org/10.3389/fevo.2023.1048768

[8] Tripathi, K., Kaur, R., et al. [2024]. Optimizing yield and water productivity in summer mung bean under irrigation management. PubMed Central. https://pmc.ncbi.nlm.nih.gov/articles/PMC11514972/

[9] Haider, M. U., Hussain, M., Farooq, M., & Nawaz, A. [2018]. Improving growth, productivity and energetics of mungbean [Vigna radiata L.] through foliar application of zinc. International Journal of Agriculture and Biology, ICAR e-Pubs. https://epubs.icar.org.in/index.php/IJAgS/article/view/154040

[10] Hossain, M. A., et al. [2023]. Foliar application of different levels of zinc and boron on the productivity of mungbean. Turkish Journal of Agriculture - Food Science and Technology, 6107. https://www.agrifoodscience.com/index.php/TURJAF/article/view/6107

[11] Farooq, M., et al. [2025]. Enhancing zinc and iron biofortification in mungbean [Vigna radiata] and associated growth/yield responses. Nature Scientific Reports, PMC11958780. https://pmc.ncbi.nlm.nih.gov/articles/PMC11958780/

[12] Ning, D., Zhang, Y., Li, X., Qin, A., Huang, C., Fu, Y., Gao, Y., & Duan, A. [2023]. The Effects of Foliar Supplementation of Silicon on Physiological and Biochemical Responses of Winter Wheat to Drought Stress during Different Growth Stages. Plants, 12[12], 2386. https://doi.org/10.3390/plants12122386

[13] Wang, et al. [2025]. Foliar fertilizer and irrigation effects on mung bean. Frontiers in Plant Science, 10.3389/fpls.2025.1704065. https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2025.1704065/full

[14] Ahmad, A., et al. [2024]. Silicon-Mediated Improvement in Drought and Salinity Stress Tolerance of Black Gram [Vigna mungo L.] by Modulating Growth, Physiological, Biochemical, and Root Attributes. ACS Omega, PMC11375724. https://pmc.ncbi.nlm.nih.gov/articles/PMC11375724/

[15] Raza, M. A., et al. [2021]. Combined application of zinc and silicon alleviates terminal drought stress in wheat by triggering morpho-physiological and antioxidants defense mechanisms. PLOS ONE, 16[10], e0256984. https://doi.org/10.1371/journal.pone.0256984

[16] Ansari, M. J., et al. [2022]. Drought stress-induced modification of morpho-anatomical and yield attributes of mung bean associated with the application of silicon and Moringa leaf extract. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 50[4], 13370. https://www.notulaebotanicae.ro/index.php/nbha/article/view/13370

[17] Waraich, E. A., et al. [2022]. Foliar Spray of Micronutrients Alleviates Heat and Moisture Stress in Lentil: Implications for Yield and Quality in Late-Sown Crops. Frontiers in Plant Science, 13, 847743. https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.847743/full

[18] Kumar, V., et al. [2023]. Zinc-induced variations in dry matter production, partitioning, and yield of mungbean [Vigna radiata L.] under water stress. International Journal of Plant, Soil and Science. https://journalijpss.com/index.php/IJPSS/article/view/5463

[19] Siad, S. M., & El-Beltagi, H. S. [2024]. Alpha lipoic acid mitigates adverse impacts of drought stress on growth and yield of mungbean: photosynthetic pigments and antioxidative defense mechanism. PeerJ, 12, 17191. https://peerj.com/articles/17191/

[20] Moustafa-Farag, M., & Edris, A. E. [2004]. Soil moisture stress and micronutrients foliar application effects on growth and yield of mung bean plants. Journal of Plant Production, 237098. https://jpp.journals.ekb.eg/article_237098.html

[21] Thombre PR, Dalvi DG, Thombre AB, Gore VB, Lagad SL. Studies on physiological traits of mungbean [Vigna radiata L.] genotypes. *The Pharma Innovation Journal*. 2023;12[12]:1046–1050. Available from: https://www.thepharmajournal.com/archives/2023/vol12issue12/PartL/12-12-182-930.pdf
[22] International Seed Testing Association [ISTA]. *International Rules for Seed Testing*. Bassersdorf, Switzerland: ISTA. Available from: https://www.seedtest.org/en/publications/international-rules-seed-testing.html
[23] R Core Team. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing; 2025. Available from: https://www.R-project.org/
[24] Bates D, Mächler M, Bolker B, Walker S. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*. 2015;67[1]:1–48. doi:10.18637/jss.v067.i01.
[25] Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*. 2017;82[13]:1–26. doi:10.18637/jss.v082.i13.
[26] Lenth R, Piaskowski J. *emmeans: Estimated Marginal Means, aka Least-Squares Means* [R package]. 2025. Available from: https://CRAN.R-project.org/package=emmeans