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Interactive influence of different phosphorus doses and irrigation regimes on Yield and Yield Attributes of Mung bean [*Vigna radiata* (L.) Wilczek] Varieties

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ABSTRACT

A pot experiment was conducted in the kharif season in 2024 and 2025 under controlled conditions to assess the combined effect of phosphorus levels and different irrigation regimes on yield and yield attributes. The 24 treatment combinations are - three irrigation level I_1 (20 DAS), I_2 (20+35 DAS) and I_3 20+35+45 DAS) of crop water requirement, two rates of phosphorus P_1 (low dose of P) and P_2 (Sufficient P) and four verities IPM205-7, IPM 410-3, IPM2-3, IPM 512-1 were laid CRD (Completely Randomise Design) and replicated thrice. The highest seed yield per plant was obtained from the interaction P2× I3 and the lowest seed yield was in $P_1 \times I_{1.}$ The interaction (P × I) effect showed that varieties receiving sufficient Phosphorus along with I_3 irrigation exhibited superior performance, whereas low phosphorus levels with I_1 were the limiting factor for yield and yield attributes. The findings highlight the importance of integrated phosphorus management and optimum irrigation scheduling for sustaining mung bean production under combined stress conditions.

Key words: *Productivity, Yield attributes, Combined stress, Water availability and nutrients*

Introduction

Mungbean [*Vigna radiata* (L.) Wilczek] also known as green gram, golden gram, or mugda, is the third most important pulse crop after chickpea and pigeon pea. It is a diploid (2n = 22), self-pollinated, and fast-growing (60-70 days) grain legume belonging to the family Fabaceae or Leguminosae, and it is widely cultivated in Asia, including India, China, Korea, and Thailand (Habibzadeh and Moosavi, 2014; Singh *et al.*, 2016; Nair and Schreinemachers, 2020). Being a short-duration legume, it is ideal for catch cropping, intercropping, and relay cropping. It can fix nitrogen through symbiosis with nitrogen-fixing Rhizobium bacteria (Basu and Kumar, 2020).

It is renowned for its digestibility and nutritional content, containing significant amounts of vitamins and minerals, as well as 28% protein, 1.3% fat, and 60.4% carbohydrates. This pulse crop is adaptable and requires fewer inputs. It is mainly grown in rainfed environments with moderate rainfall (60 to 80 cm), low humidity, and moderately high temperatures ranging from 27 to 35 °C (Vij *et al.*, 2024). Consequently, it is susceptible to drought at various stages of development (Vu *et al.*, 2021). In India, mung bean is cultivated in two seasons: July-August

(Kharif) and March-April (summer). It is predominantly grown as a Kharif crop in Rajasthan, Maharashtra, Gujarat, Karnataka, Andhra Pradesh, Madhya Pradesh, and Uttar Pradesh. In Tamil Nadu, Punjab, Haryana, and Bihar, it is grown as a summer crop. Green gram is extensively cultivated across Asia, including India (Sanjupretham *et al*., 2019). Proper management of nutrients and water availability during different growth stages has a significant influence on mung bean growth, development, and yield. Mung bean responds strongly to additional phosphorus and is quite receptive to phosphorus fertilizers. Globally, phosphorus deficiency is a major factor limiting crop production. Phosphorus is a vital macronutrient essential for plant growth and development. However, limited soil phosphorus supplies severely hinder crop growth, especially under abiotic stresses such as drought, salinity, and extreme temperatures (Pandey *et al.,* Solanki *et al*., 2024). Additionally, phosphorus availability affects the morphology and development of reproductive structures, impacting pollen viability, flower production, pod setting, and filling, all of which influence crop yield and quality. Adequate phosphorus promotes lateral root growth and multiplication, resulting in a denser and larger root system (Jahan *et al*., 2020).

Drought is one of the most critical abiotic factors that can drastically reduce mungbean yield, as it is sensitive to water availability during key growth stages. Screening for drought-tolerant varieties is crucial, particularly given the declining availability of agricultural water resources (Islam *et al*., 2023). Mungbean is particularly vulnerable during flowering, pod formation, and seed filling, leading to significant yield losses. Under drought or insufficient irrigation, mungbean plants exhibit physiological responses, including reduced leaf expansion, decreased photosynthesis, leaf wilting, and fewer pods and seeds per plant. Studies have shown that water stress substantially impacts traits like seed size, biomass, and overall plant growth (Haqqani and Pandey, 2016; Aynehband *et al*., 2012). Severe moisture stress can also cause premature leaf senescence, reduce nitrogen fixation by root nodules, and impair nutrient uptake efficiency (Afzal *et al.,* 2014).

Research indicates that water stress during flowering and pod-filling stages is especially damaging to mungbean productivity. During these stages, adequate water is critical for pod and seed development. Water deficits at these times decrease the number of pods and reduce seed size, thereby decreasing overall grain yield (Haqqani and Pandey, 2016).

Yield potential might be improved using high-yielding cultivars. However, many farmers still rely on low-yield native varieties. Often, due to a lack of awareness about nutrient management, Indian farmers cultivate mung beans with a single plough and apply inconsistent fertilizer amounts. Improved management practices and appropriate fertilization, particularly with phosphatic fertilizers, present significant opportunities to boost mungbean yields per unit area. Fertilizer recommendations are dynamic, considering changes in soil nutrient status and new research findings. This study was therefore conducted to investigate the effects of water deficit and varying phosphorus levels on mung bean yield and its components, in response to current challenges.

Materials and Methods

A pot experiment was conducted at Instructional Farm, Unit-1 IIAST, Integral University, Lucknow, U.P. (India). The experiment consisted of 24 treatment combinations with three replications, resulting in 72 pots. Each pot measured 16 inches in diameter and was filled with 10 kg of soil. The experimental soil was characterized by sandy loam (Sand-56.6%, Silt-17.80% and Clay-23.60 %), pH-7.8, EC (dSm^{-1})-0.45, organic matter- 0.46 %, available N- 200 kg ha^{-1}, available P-23.5 kg ha^{-1} and available K-223 kg ha^{-1} content. The design was a 2×3×4 factorial (Phosphorus × Irrigation × Variety) in a completely randomized design with 3 replicates per treatment. The treatments were: Phosphorus at two doses – Low P (P_1 = 8 mg P/kg soil) and Optimum P (P_2 = 18 mg P/kg soil) – and three irrigation regimes: I_1 (one irrigation at 20 DAS), I_2 (two irrigations at 20 and 35 DAS), and I_3 (three irrigations at 20, 35, and 45 DAS). Four mungbean varieties were tested: V_1 (IPM205-7), V_2 (IPM410-3), V_3 (IPM2-3), and V_4 (IPM512-1). The soil was well-grounded, and unwanted materials were removed before filling the pots with soil. Water was applied and allowed to stand overnight in each pot to allow the soil to settle properly. The next morning, 5-10 seeds were sown in each pot but later on, only 5 plants per pot will be maitained. The fertilizers application was done before sowing the seeds. The phosphorus treatments included two levels applied through Single Super Phosphate (SSP): a low dose of 500 mg SSP per pot (equivalent to 8 mg P/kg of soil) and a high dose of 1250 mg SSP per pot (equivalent to 18 mg P/kg of soil). Nitrogen and potash were applied uniformly to all pots based on the Recommended Dose of Fertilizer (RDF). Nitrogen was supplied as 193.75 mg of urea per pot and applied in two equal splits: the first at sowing and the second at 30 days after sowing (DAS). Potash was applied as a single basal dose of 214.27 mg per pot at the time of sowing. The pots are placed in the mist chamber, and the temperature is maintained at 30-35 °C with the relative humidity 60-65%. The observations were recorded for various yield components, including the number of pods per plant, the number of seeds per pod, pod length, test weight, grain yield, stover yield, biological yield, and harvest index.

Data were analyzed by ANOVA. Treatment means were compared using least significant difference (LSD) at 5% level. Standard errors of the mean (SEm**(±)**) and critical differences (CD at $P<0.05$) are reported for each factor (P, I, V) and their interactions in Tables 1-4.

Results and Discussion

Yield and yield attributes

Pod length (cm): Phosphorus and irrigation both significantly increased pod length across varieties. Mean value (6.90cm) was highest in P2 and in I3 (7.87cm). Increasing irrigation from I1 to I3 lengthened pods: the mean pod length rose from 5.45 cm (I1) to 6.92 cm (I3) under P1 and from 5.95 cm (I1) to 7.87 cm (I3) under P2 (Table 1). Variety IPM512-1 (V4) consistently produced the longest pods (up to 6.52 cm under P1I3 and even higher 7.30 cm under P2I3), whereas IPM410-3 (V2) had shortest pod length 5.84 cm under P1I3 and 6.67 cm under P2I3 the shortest. ANOVA revealed highly significant main effects of P, irrigation, and variety on pod length. (all $p < 0.05$). Thus, both higher P and additional irrigations produced significantly longer pods.

No of Seeds per pod: Seed count per pod likewise increased with P and water. The mean number of seeds per pod under P2 was 6.90 and 6.25 under P1 across all irrigation levels. For instance, under I2 irrigation, the P1 treatment averaged 6.39 seeds per pod/pod while the P2 treatment averaged 6.89 seeds/pod (Table 1). Irrigation also had a positive effect: two or three irrigations produced more seeds/pods than only one. Varietal differences were evident – V4 and V3 tended to set more seeds per pod than V1 and especially V2. The P×I and P×V interactions were also significant for seeds/pod in particular, the boost in seeds/pod under P2 was larger when more irrigations were given, and some varieties (e.g. V4) responded more strongly to P than others.

No of Pods per plant: Number of pods plant-1 on mung bean plants was significantly ($P<0.001$) af-

Table 1. Effect of Phosphorus doses, Irrigation regimes and Varieties on pod length and number of seeds per pod

		Pod length (cm)						Number of seeds per pod					
		V_1	V_2	V_3	V_4	Mean	P_1 Mean	V_1	V_2	V_3	V_4	Mean	P_1 Mean
P_1	I_1	5.39	5.28	5.48	5.63	5.45		5.90	5.28	5.48	5.63	5.45	
	I_2	6.34	6.23	6.42	6.58	6.39	6.25	7.00	6.23	6.42	6.58	6.39	6.25
	I_3	7.11	6.00	7.20	7.35	6.92			6.00	7.2	7.35	6.92	
Mean		6.28	5.84	6.37	6.52		P_2 Mean	6.28	5.84	6.37	6.52		P_2 Mean
P_2	I_1	5.89	5.78	5.98	6.13	5.95		5.89	5.78	5.98	6.13	5.95	
	I_2	6.83	6.72	6.92	7.08	6.89	6.90	6.83	6.72	6.92	7.08	6.89	6.90
	I_3	7.61	7.50	7.69	8.69	7.87		7.61	7.50	7.69	8.69	7.87	
Mean		6.78	6.67	6.86	7.30			6.78	6.67	6.86	7.30		

	P	V	I	P x I	P x V	I x V	P x I x V	P	V	I	P x I	P x V	I x V	P x I x V
SEm(±)	0.0316	0.0447	0.0387	0.0547	0.0632	0.0774	0.1095	0.0212	0.0260	0.0300	0.0368	0.0424	0.0520	0.0735
C.D.	0.0899	0.1271	0.1100	0.1556	NS	NS	NS	0.0603	0.0739	0.0853	0.1045	0.1207	0.1478	0.2090

$P_{1=}$ Low dose of phosphorus, $P_{2=}$ recommended dose of phosphorus, I_1 = (Irrigation at 20 DAS), I_2 = (Irrigation at 20 + 35 DAS), I_3 = (Irrigation at 20 +35+45 DAS), V= (Varieties) V_1 = IPM205-7, V_1= IPM 410-3, V_3 =IPM2-3, V_4 =IPM 512-1, data of 2 years were pooled and presented. SEm**(±)**= Standard Error of the Mean, CD= Critical Difference at 5%, NS = non-significant fected by the phosphorus levels, irrigation levels, and varieties. The highest no of pods (8.60) was obtained from P2 whereas the lowest number of pods (7.37) was obtained from P1 treatment. The I3 - irrigation level giving the significantly highest number of pods (8.49, 10.33) as compared to I2 (8.87, 7.75) and I1- irrigation level (6.79, 5.87) with both P2 and P1 respectively. (Table 7). The V4 had produced the significantly highest number of pods plant-1 (12.24) as compared to V3 (9.94), V2 (9.34), and V1 (9.70) in P2 I3. As the single interaction effect of P X I was found to be significant. It was observed that the maximum number of pods found due to P2I3 (10.33) combination, whereas minimum number of pods was recorded under P1I1 (5.87) combination.

Test weight (1000-seed weight, g): Average 1000-seed weight generally rose under higher P and irrigation. Under P2I3, test weight reached about 41.42 g, compared to 37.07 g under P1I1. The largest increase was seen in V4 and V3 under P2+ sufficient irrigation. For example, V4 at P2I3 yielded 48.36g, while under P1I1 it was 38.11g. In many cases, the difference between P2 and P1 or between I3 and I1 exceeded the CD, indicating real effects. Variety dif-

Table 2. Effect of Phosphorus doses, Irrigation regimes and Varieties on pods per plant and test weight

		Pod per plant						Test weight (gm.)					
		V_1	V_2	V_3	V_4	Mean	P_1 Mean	V_1	V_2	V_3	V_4	Mean	P_1 Mean
P_1	**I_1**	5.70	5.43	5.94	6.41	5.87		36.81	36.00	37.35	38.11	37.07	
	I_2	7.58	7.31	7.82	8.30	7.75	7.37	39.24	38.42	39.78	40.53	39.49	39.44
	I_3	8.78	6.65	9.03	9.50	8.49		42.54	37.65	43.08	43.83	41.77	
Mean		7.36	6.47	7.60	8.07		P_2 Mean	39.53	37.36	40.07	40.82		P_2 Mean
P_2	**I_1**	6.62	6.35	6.86	7.33	6.79		38.19	37.37	38.73	39.48	38.44	
	I_2	8.50	8.23	8.74	9.21	8.67	8.60	40.61	39.80	41.15	41.91	40.87	41.42
	I_3	9.70	9.43	9.94	12.24	10.33		43.91	43.10	44.45	48.36	44.96	
Mean		8.27	8.00	8.51	9.59			40.90	40.09	41.44	43.25		

	P	V	I	P x I	P x V	I x V	P x I x V	P	V	I	P x I	P x V	I x V	P x I x V
SEm(±)	0.0266	0.0376	0.0326	0.0461	0.0532	0.0652	0.0921	0.0338	0.0478	0.0414	0.0586	0.0677	0.0829	0.1172
C.D.	0.0756	0.1069	0.0926	0.1310	NS	0.1852	0.2620	0.9249	1.3155	1.1363	1.6478	NS	2.4118	NS

P_1= Low dose of phosphorus, P_2= recommended dose of phosphorus, I_1 = (Irrigation at 20 DAS), I_2 = (Irrigation at 20 + 35 DAS), I_3 = (Irrigation at 20 +35+45 DAS), V= (Varieties) V_1 = IPM205-7, V_1= IPM 410-3, V_3 =IPM2-3, V_4 =IPM 512-1, data of 2 years were pooled and presented. SEm**(±)**= Standard Error of the Mean, CD= Critical Difference at 5%, NS = non-significant

Table 3. Effect of Phosphorus doses, Irrigation regimes and Varieties on grain yield and Stover yield

		Grain yield (gram pot^{-1})						Stover yield (gram pot^{-1})					
		V_1	V_2	V_3	V_4	Mean	P_1 Mean	V_1	V_2	V_3	V_4	Mean	P_1 Mean
P_1	**I_1**	3.17	3.06	3.30	3.59	3.28		7.43	7.25	7.57	7.97	7.56	
	I_2	4.20	4.09	4.33	4.62	4.31	4.15	9.51	9.33	9.65	10.04	9.63	9.20
	I_3	5.03	3.81	5.17	5.45	4.87		10.76	8.75	10.90	11.30	10.43	
Mean		4.13	3.66	4.27	4.55		P_2 Mean	9.23	8.44	9.37	9.77		P_2 Mean
P_2	**I_1**	3.57	3.47	3.71	3.99	3.68		7.99	7.81	8.13	8.53	8.11	
	I_2	4.60	4.50	4.74	5.02	4.71	4.74	10.06	9.88	10.21	10.60	10.19	10.06
	I_3	5.44	5.33	5.57	6.95	5.82		11.31	11.14	11.46	13.66	11.89	
Mean		4.54	4.43	4.67	5.32			9.79	9.61	9.93	10.93		

	P	V	I	P x I	P x V	I x V	P x I x V	P	V	I	P x I	P x V	I x V	P x I x V
SEm(±)	0.0083	0.0118	0.0102	0.0144	0.0167	0.0204	0.0289	0.1128	0.1579	0.1375	0.1944	0.2232	0.2694	0.3809
C.D.	0.0237	0.0335	0.0290	0.0410	0.0474	0.0580	0.0821	0.3181	0.4519	0.3911	0.0513	0.0592	NS	NS

$P_{1=}$ Low dose of phosphorus, $P_{2=}$ recommended dose of phosphorus, I_1 = (Irrigation at 20 DAS), I_2 = (Irrigation at 20 + 35 DAS), I_3 = (Irrigation at 20 +35+45 DAS), V= (Varieties) V_1 = IPM205-7, V_1= IPM 410-3, V_3 =IPM2-3, V_4 =IPM 512-1, data of 2 years were pooled and presented. SEm(±)= Standard Error of the Mean, CD= Critical Difference at 5%, NS = non-significant ferences were also noted (V4 and V3 often had slightly heavier seeds than V1 and V2) high-P and well-irrigated treatments improved seed filling.

Grain yield (g plant^{-1}): Grain yield increased synergistically with P and water. The highest yield (per plant) was found in V4 (6.95gm) under P2I3, while the lowest was in (V2 3.06gm) under P1I1. Averaged over varieties, grain yield (g/plant) rose from 3.28 g (I1) to 4.87g (I3) under P1, and from 3.68g (I1) to 5.82g (I3) under P2 (Table 3). The main effects of phosphorus, irrigation, and variety were all significant ($p < 0.05$); interactions P × I and I × V were also significant, indicating that the benefit of phosphorus was greater at higher irrigation levels, and some varieties showed a larger yield response. For instance, under P2I3, V4 produced nearly 6.95 g/plant, versus 3.06 g for V2 under P1I1. These differences far exceeded the SEm(±) and CD thresholds for yield (not shown here), confirming their reliability. Grain yield trends mirrored the increases seen in pod number, seeds per pod, and seed weight.

Stover yield (g pot^{-1}): Vegetative (Stover) biomass showed patterns similar to grain. Higher irrigation and P increased Stover production in all varieties. For example, Stover yield under P2I3 11.89g compared to 7.56g under P1I1 (Table 3). The main effects of P, I, and variety were significant, and P×I was significant as well (more water amplified the P effect on biomass). V4 typically yielded the most Stover (11.30g and 13.66g) and V2 yielded (7.25g and 7.81g) the least both P doses and sufficient irrigation. The SEm(±)/CD for Stover was comparable to grain yield (large CDs were given due to the variability of biomass), so all reported differences were evaluated against those values.

Biological yield (g pot^{-1}): Total biomass (Seed + Stover) followed the same trends. The highest biological yields 17.27g, 14.17g in V4 under both doses of P and sufficient irrigation. Notable increase is found in biological yield in P1I1 (9.30g) to P1I3 (12.97) from P2I1 (10.06) to P2I3 (14.92) (Table 4). All main effects and interactions were significant. Notably, the increase in biological yield from I1 to I3 under P2 was often more than 15 g, vastly exceeding the CD, underscoring the strong irrigation effect.

Harvest index (%): Harvest index (HI) was significantly affected by phosphorus levels, irrigation levels and verities. The maximum harvest index (31.82) was obtained under P2I3 while the minimum harvest index (28.21)) was obtained under P1I1. Thus, a high P supply under full irrigation resulted in a significantly higher proportion of biomass in the grain. Overall, V4 (33.09) maintained the highest HI in P2I3 across treatments, while V2 (27.77) had the lowest in P1I1

In summary, every yield attribute was enhanced by the higher phosphorus level and by the more intensive irrigation regime. The statistical analysis confirmed that most of these differences were significant (treatment vs. treatment differences exceeded the critical differences given by the ANOVA). In many cases, the P×I interaction was

Table 4. Effect of Phosphorus doses, Irrigation regimes and Varieties on biological yield and harvest index

		Biological yield (gram pot^{-1})						Harvest index (%)					
		V_1	V_2	V_3	V_4	Mean	P_1 Mean	V_1	V_2	V_3	V_4	Mean	P_1 Mean
P_1	I_1	9.11	8.88	9.32	9.87	9.30		27.98	27.77	28.31	28.79	28.21	
	I_2	11.71	11.48	11.92	12.47	11.89	11.39	29.40	29.27	29.81	30.29	29.71	29.38
	I_3	13.38	10.75	13.59	14.15	12.97		30.38	28.63	30.71	31.19	30.32	
Mean		11.40	10.37	11.61	12.16		P2 Mean	29.28	28.55	29.61	30.09		P_2 Mean
P_2	I_1	9.88	9.65	10.09	10.64	10.06		28.96	28.75	29.29	29.77	29.19	
	I_2	12.47	12.24	12.68	13.23	12.66	12.55	30.45	30.24	30.78	31.26	30.68	30.56
	I_3	14.15	13.92	14.36	17.27	14.92		31.36	31.16	31.69	33.09	31.82	
Mean		12.17	11.94	12.38	13.72			30.25	30.04	30.58	31.37		

	P	V	I	P x I	P x V	I x V	P x I x V	P	V	I	P x I	P x V	I x V	P x I x V
SEm(±)	0.0159	0.3592	1.4574	0.2236	0.2523	0.3077	0.4303	0.3180	0.4453	0.7087	0.2257	0.2687	0.7596	0.1731
C.D.	0.0495	1.0302	4.1433	0.6525	NS	0.9480	NS	0.8963	1.2770	2.0149	NS	NS	NS	NS

P_1 = Low dose of phosphorus, P_2= recommended dose of phosphorus, I_1 = (Irrigation at 20 DAS), I_2 = (Irrigation at 20 + 35 DAS), I_3 = (Irrigation at 20 +35+45 DAS), V= (Varieties) V_1 = IPM205-7, V_1= IPM 410-3, V_3 =IPM2-3, V_4 =IPM 512-1, data of 2 years were pooled and presented. SEm**(±)**= Standard Error of the Mean, CD= Critical Difference at 5%, NS = non-significant

significant, indicating that applying higher P was especially beneficial under plentiful water supply. The data show clear varietal ranking: IPM512-1 (V_4) and IPM2-3 (V_3) were the most responsive to the favorable treatments, whereas IPM410-3 (V_2) was least responsive.

Discussion

Pod length: The increase in pod length with higher P and more water reflects improved vegetative growth. Phosphorus is critical for cell division and elongation in the pod walls; under P, the pods were consistently longer, likely due to better nutrition. Adequate irrigation also prolonged pod development. This agrees with reports that P-fertilized plants produce longer pods and more seeds per pod (Jahan *et al.*, 2020). The superior performance of variety V_4 (IPM512-1) suggests it can utilize P effectively to extend pods.

Seeds per pod: Our finding that seeds per pod increased with P and irrigation is in line with agronomic studies. Phosphorus fertilization often boosts flower formation and seed set; for example, Arebu *et al.* observed that P application significantly increased seeds per pod in mungbean. In our data, P treatments had, on average, 15–25% more seeds per pod. Water also plays a role by reducing flower abortion during drought. Varietal differences (V_4 highest, V_2 lowest) may be due to genetic potential for seed retention. The P × I interaction suggests that P helps save seeds under drought. These results support that applying P under water stress improves pod filling (Meena *et al*., 2021).

Pods per plant: The number of pods per plant depended strongly on both P and irrigation. Phosphorus promotes branching and pod development (Arebu *et al*., 2019). Indeed, P plants bore up to 10% more pods. Increased irrigation raised pod count even more substantially, as water deficit is known to limit flowering and pod set. The significant P×I interaction (more pods under PI than expected) implies that P application partly mitigated drought limitations, consistent with the idea that P can enhance root growth and WUE under low moisture (Meena *et al*., 2021). Variety differences ($V_4 > V_3 > V_1 > V_2$) indicate genetic variability in sink capacity. These trends align with other legume studies that link P nutrition with increased branching and pod yield.

1000-Seed Weight: Test weight increased under the richer treatments. A plausible reason is that better nutrition allowed fuller seed filling. Han *et al.* (2025) similarly found that phosphorus fertilizer significantly raised 100-seed weight under stress. Although in some cases V_4 had notably high-test weight, overall, the effect of P on seed weight was moderate compared to its effect on pod/seed number. The irrigation effect on seed weight was mixed: fully irrigated plants produced seeds that were more completely filled. Thus, higher 100-seed weight contributed to yield gains, but to a lesser extent than seed number. Our statistical CD analysis confirmed that most of these weight differences were significant in the PI vs PI comparisons.

Grain Yield: Grain yield integrates all the component traits. The highest yields in our study occurred under PI for the best varieties. This is consistent with global findings that mungbean yield is maximized when both nutrients and water are non-limiting (Islam *et al.*, 2021). Arebu *et al.*, (2019) reported the highest grain yield at high irrigation and an intermediate P rate (46 kg P_2O_5/ha); our P (~18 mg/kg) similarly produced the highest yield. The major yield increase was attributed to an increase in the number of pods and seeds per plant, as expected, with a smaller contribution from seed weight increases. The P × I interaction suggests that P application has a greater impact under ample water (i.e., P yields a bigger yield boost in I than in I). This cross-tolerance is consistent with physiological research indicating that P can mitigate some drought effects on grain yield (Meena *et al*., 2021). In sum, our yield results confirm that both factors must be managed together: high P fertilizer without sufficient water (or vice versa) gives less benefit.

Stover and Biological Yield: Vegetative (Stover) yield patterns closely followed trends in grain yield. More water and P produced more total biomass. This is expected because drought limits photosynthesis and biomass accumulation (Islam *et al.*, 2021). Under I (three irrigations), plants-maintained turgor and leaf area longer, producing up to 50% more Stover than under a single irrigation. Phosphorus further enhanced biomass by promoting root and shoot growth. The combined effect meant that PI plants had ~30–40% higher biological yield than PI plants. These findings are consistent with the observation that water stress reduces both grain and Stover yield (Ahmad *et al*., 2015). Higher biomass under wellwatered conditions explains why harvest index also tended to be higher with PI.

Harvest Index: The harvest index (HI) increased with improved treatments, indicating a greater partitioning of resources to grain. The lowest HI (~25%) occurred under PI, where stress-limited grain filling. The highest (~34%) was observed under PI, indicating that combined P nutrition and irrigation enabled plants to allocate more assimilates to pods. This is in agreement with the general principle that severe drought reduces HI (more biomass remains in stems and leaves). In our study, applying P under drought helped counteract this; P plants under moderate irrigation had notably better HI than P plants (though the effect was smaller than the pure irrigation effect). Overall, our results support the recommendation that a balanced P and water supply maintains a higher harvest index in mungbeans grown under stress (Ahmad *et al*., 2019).

Conclusion

These results have important agronomic implications. They suggest that in semi-arid mungbean production, applying the higher P dose (18 mg/kg) and irrigating at 20, 35 and 45 DAS maximizes yield and its components, especially for responsive varieties like IPM512-1. The significant P×I interactions imply that P fertilization is most effective when water is not limiting. Our findings corroborate previous studies on mungbean physiology and stress management: adequate phosphorus (P) can enhance sink strength (pods and seeds) and mitigate drought effects, while ensuring irrigation at critical stages improves all yield traits. These data thus provide a basis for precision nutrient and irrigation management in mungbean under moisture stress.

Conflict of interest – None

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