RESPONSE OF KHARIF MUNGBEAN (*VIGNA RADIATA* L. WILCZEK) TO GRADED LEVELS OF POTASSIUM FERTILIZATION ACROSS EIGHT AGRO-ECOLOGICAL LOCATIONS OF PUNJAB, PAKISTAN

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ABSTRACT

Mungbean (*Vigna radiata* L. Wilczek) is the most important Kharif pulse crop of Pakistan, yet on-farm yields across Punjab remain well below the genetic potential of currently released varieties. The persistent yield gap has been linked to the widespread practice of growing mungbean as a low-input crop on residual soil fertility, with little or no application of macronutrients other than starter nitrogen. The present study was conducted under the Soil Fertility Punjab research project PLAN-10 to evaluate the response of Kharif mungbean (cv. AZRI-Mung 2021) to graded levels of soil-applied potassium fertilization at eight agro-ecological locations of Punjab during the 2024 Kharif season. Six treatments; an absolute no-fertilizer control (T1); a nitrogen–phosphorus basal alone (T2; 62.5 kg N + 86 kg P_2O_5 ha^{-1}); and four NP plus graded K_2O treatments at 30, 40, 50, and 60 kg K_2O ha^{-1} supplied as sulphate of potash (T3–T6), were arranged in a randomized complete block design with three replications at each site. Combined analysis of variance revealed highly significant effects of location, treatment, and their interaction on both grain yield and thousand grain weight ($p < 0.01$ for all terms). Pooled across the eight sites, grain yield rose progressively from 841.6 kg ha^{-1} at the absolute control to 1,265.6 kg ha^{-1} under the NP basal alone (+50.4%) and to 1,545.8 kg ha^{-1} at the highest K rate (+83.7% over the absolute control, and a further +22.1% over the NP-only baseline). The yield response was monotonically positive at every site, peaked at 60 kg K_2O ha^{-1} in all eight locations, and showed no evidence of a plateau. The site-wise yield gain over the absolute control ranged from +505 kg ha^{-1} at Bhakkar to +890 kg ha^{-1} at Faisalabad. On this evidence, the inclusion of 60 kg K_2O ha^{-1} as a basal soil-applied input (alongside 62.5 kg N + 86 kg P_2O_5 ha^{-1}) is recommended as a regional fertilization practice for Kharif mungbean across Punjab; the still-rising response curve further suggests that even higher K rates warrant testing on these soils.

Key words: Mungbean, potassium fertilization, AZRI-Mung 2021, multi-location trial, Punjab.

INTRODUCTION

Mungbean (*Vigna radiata* L. Wilczek) is the most widely grown summer pulse of South Asia and the most important Kharif legume of Pakistan, valued for its short crop cycle (60–75 days), capacity to fix atmospheric nitrogen through symbiosis with *Bradyrhizobium*, and protein-rich grain that constitutes a staple component of regional diets (Nair *et al*., 2019). The crop is cultivated on approximately 185,000 hectares in Pakistan, with Punjab accounting for the bulk of the national area and production (GoP, 2025). Beyond its direct value as a pulse, mungbean plays a strategic role in cereal-based cropping systems through residual soil-nitrogen contributions to the following wheat or rice crop, and its inclusion in rotations has been documented to enhance soil organic matter, microbial activity, and the productivity of subsequent cereal crops (Ali and Gupta, 2012; Nair *et al.*, 2019). Despite this strategic importance, on-farm mungbean yields in Pakistan have remained persistently low at 600–900 kg ha^{-1}, well below the 1,500–2,000 kg ha^{-1} potential of currently released varieties, and the yield gap has shown only marginal narrowing over the past two decades (Sehrawat *et al.*, 2019).

One of the primary drivers of the yield gap is the dominant practice of growing mungbean as a low-input crop on residual soil fertility. Smallholder growers across Punjab routinely sow mungbean immediately after a winter

wheat or oilseed crop with little or no fertilizer application, on the implicit assumption that the legume's biological N-fixation will substitute for soil nutrient supply (Imtiaz *et al.*, 2011). While N-fixation does reduce mungbean's exogenous nitrogen requirement, the assumption that other macronutrients can also be neglected is increasingly difficult to sustain on Pakistan's alkaline-calcareous soils, where decades of intensive cereal cropping have progressively depleted plant-available pools of potassium and phosphorus (Rashid and Ryan, 2004; Imran *et al.*, 2020). Modern high-yielding mungbean cultivars carry substantially higher nutrient removal coefficients than traditional landraces, and their realized yield potential cannot be expressed under fully unfertilized field conditions.

Of the major macronutrients required by mungbean, potassium has received comparatively little experimental attention in Pakistan. Potassium is the principal cation regulating stomatal aperture, phloem loading of sucrose and amino acids, enzyme activation in carbohydrate and protein metabolism, and osmotic adjustment under heat and water stress, all functions of particular importance in legumes maturing under high-temperature, late-season conditions (Hawkesford *et al.*, 2012; Hasanuzzaman *et al.*, 2018). In nodulating legumes, adequate K supply has additionally been linked to improved nodule formation and function, enhanced biological nitrogen fixation efficiency, and greater partitioning of photo-assimilate to developing pods (Sangakkara *et al.*, 1996; Wang *et al.*, 2013; Yu *et al.*, 2022). For mungbean specifically, calibrated K dose–response data on Pakistani alkaline soils are sparse, and the question of whether K fertilization on top of an N+P baseline produces an agronomically meaningful and reproducible yield gain across the diverse agro-ecological zones of Punjab has not previously been answered through a properly replicated multi-location trial.

Soil potassium availability in Punjab is heterogeneous. Reviews and country-scale syntheses have repeatedly classified roughly one-third of Pakistani soils as deficient or marginal in available potassium, with the strongest deficiencies recorded on coarse-textured, low-organic-matter soils of the Thal and Cholistan tracts and on intensively cropped fine-textured soils of central Punjab (Hasanuzzaman *et al.*, 2018). Soil-K test values alone, however, are an imperfect predictor of crop response, because K availability is jointly controlled by soil texture, exchangeable K, non-exchangeable K reserves, and the kinetics of K release from clay-mineral interlayers under field conditions (Hawkesford *et al.*, 2012). The question of whether mungbean yield responds to K fertilization across the contrasting soils of Punjab therefore requires empirical, multi-location dose–response testing rather than inference from soil-test data alone (Yin *et al.*, 2018).

The present study was conducted under the Soil Fertility Punjab research project PLAN-10 ("Mung response to potassium") to evaluate the response of Kharif mungbean (cv. AZRI-Mung 2021) to four graded levels of soil-applied potassium fertilization, against both an absolute no-fertilizer control and an N+P basal control, at eight agro-ecological locations spanning the southern, central, and Thal regions of Punjab during the 2024 Kharif season. The specific objectives were (i) to quantify the yield response of Kharif mungbean to graded K fertilization on top of a uniform N+P basal, in terms of both grain yield and thousand grain weight; (ii) to compare the K response against the response to N+P alone, so that the relative contributions of the three macronutrients to the observed yield improvement could be partitioned; (iii) to test whether the K response is consistent across the contrasting soils of Punjab through a formal location × treatment interaction analysis; and (iv) to identify the agronomically optimal K rate within the tested range for regional fertilizer recommendation.

MATERIALS AND METHODS

Experimental sites

The field experiment was conducted during the 2024 Kharif crop season at eight agro-ecological locations spanning the southern, central, and Thal regions of Punjab, Pakistan: Faisalabad (central Punjab), Bahawalpur (southern Punjab), Layyah (Thal), three sites in Mianwali (Mianwali-1, Mianwali-2, and Mianwali-3, representing the Thal–Salt Range transition), Bhakkar (Thal), and Khushab (Pothwar–Thal margin). All sites were managed under canal-irrigated, semi-arid to arid conditions typical of the Indus Basin cropping plain. The experiment was conducted under the framework of the Soil Fertility Research Institute (SFRI), Lahore, Punjab research project PLAN-10 ("Mung response to potassium"). Prior to land preparation at each site, composite soil samples were collected from the 0–15 cm surface layer following standard auger sampling procedures (Ryan *et al.*, 2001). Samples were air-dried, ground, sieved through a 2 mm screen, and analyzed for electrical conductivity of the saturation extract (EC_e) by conductivity meter, pH (1:1 soil-to-water suspension) by glass electrode, organic matter by the Walkley–Black wet oxidation method, available phosphorus by the AB-DTPA extraction procedure, exchangeable potassium by ammonium acetate extraction followed by flame photometry, and textural class by the hydrometer method (Ryan *et al.*, 2001; Estefan *et al.*, 2013). The soil analytical data for the eight experimental sites are presented in Table 1.

The eight sites carried predominantly loam-textured soils (with the exception of Bhakkar, which was sandy loam), neutral-to-alkaline in reaction (pH 7.50–8.30), and uniformly low in organic matter (0.41–1.13%). Electrical conductivity varied from non-saline (0.58 dS m^{-1} at Bhakkar and 0.65 dS m^{-1} at Layyah) to moderately saline (2.50–2.60 dS m^{-1} at Bahawalpur and Mianwali-2). Available phosphorus was uniformly low across all sites (5.0–7.5 ppm), and available potassium ranged from 124 ppm at Bhakkar to 200 ppm at Layyah. The soil texture, alkaline reaction, low organic matter content, and broadly low-to-medium available macronutrient pools collectively represent the agro-ecological diversity of the Punjab mungbean tract, providing a natural fertility gradient against which the consistency of the K response could be tested.

Table 1. Surface (0–15 cm) soil physico-chemical properties of the eight experimental sites.

Location	EC (dS m^{-1})	pH	OM (%)	Available P (ppm)	Available K (ppm)	Texture
Faisalabad	2.14	7.50	1.13	7.5	190	Loam
Bahawalpur	2.60	7.92	0.41	6.7	141	Loam
Layyah	0.65	8.30	0.63	7.4	200	Loam
Mianwali-1	1.60	8.30	0.50	5.0	180	Loam
Mianwali-2	2.50	8.30	0.84	5.0	180	Loam
Mianwali-3	2.40	8.20	0.58	6.5	180	Loam
Bhakkar	0.58	8.20	0.42	6.4	124	Sandy loam
Khushab	1.64	7.80	0.75	5.8	157	Loam

Plant material

The mungbean variety AZRI-Mung 2021, released by the Arid Zone Research Institute (AZRI), Pakistan Agricultural Research Council (PARC), Bhakkar, was used at all eight locations. AZRI-Mung 2021 is a short-duration, synchronously-maturing variety with documented tolerance to mungbean yellow mosaic virus (MYMV) and adaptation to Kharif sowing under the semi-arid conditions of the Punjab cropping plain. Disease-free, certified seed of uniform germination was procured from authorized seed sources and used for sowing at all sites.

Treatments and experimental design

The experiment evaluated six treatments comprising a graded series of potassium fertilization rates applied over a uniform nitrogen–phosphorus basal dose, against an absolute no-fertilizer control. The treatments were: T1 = absolute control (no fertilizer); T2 = NP basal alone (62.5 kg N + 86 kg P_2O_5 ha^{-1}, no K_2O); T3 = NP + 30 kg K_2O ha^{-1}; T4 = NP + 40 kg K_2O ha^{-1}; T5 = NP + 50 kg K_2O ha^{-1}; and T6 = NP + 60 kg K_2O ha^{-1}. Nitrogen was applied as urea, phosphorus as di-ammonium phosphate (DAP), and potassium as sulphate of potash (SOP, K_2SO_4; 50% K_2O and approximately 18% S by mass). The use of SOP as the K source additionally supplied sulphur in proportion to the K rate, an aspect considered in the interpretation of the K response. Treatment compositions are summarized in Table 2.

Table 2. Treatment compositions used to study the response of Kharif mungbean to potassium fertilization.

Treatment	Code	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
Absolute control (no fertilizer)	T1	0	0	0
NP basal alone (no K)	T2	62.5	86	0
NP + 30 kg K_2O	T3	62.5	86	30
NP + 40 kg K_2O	T4	62.5	86	40
NP + 50 kg K_2O	T5	62.5	86	50
NP + 60 kg K_2O	T6	62.5	86	60

The experiment was laid out as a randomized complete block design (RCBD) at each site, with three replications. Data from the eight sites were subsequently combined and analyzed as a two-factor combined ANOVA with locations and treatments as the two factors. The same randomization protocol was followed at all eight sites. Individual plot size was 250 m^2, equivalent to one-fortieth of a hectare, which accommodated a representative net plot area after exclusion of border rows.

Crop management

Mungbean was sown during the last week of May 2024 at all eight locations, following the recommended Kharif sowing window for AZRI-Mung 2021 in Punjab. At sowing, the full doses of P_2O_5, K_2O, and approximately 54% of the total nitrogen were broadcast uniformly over the prepared seedbed and incorporated into the surface soil through a final shallow tillage operation immediately before sowing. The remaining 46% of nitrogen was applied as a top-dressing before flowering, corresponding to the standard PLAN-10 N-application protocol. Seed was placed in opened furrows at the recommended depth and spacing for mungbean, and a uniform plant population consistent with standard production recommendations was maintained through manual thinning at the early vegetative stage. Irrigation was applied through the canal supply system: the first irrigation was given immediately after sowing to ensure uniform germination, with subsequent irrigations applied at critical growth stages including branching, flowering, and pod-filling, with frequency adjusted to crop demand, evaporative demand, and rainfall. Weeds were controlled by a combination of pre-emergence herbicide application and one manual hoeing during the early vegetative phase. Plant protection measures against jassid (*Empoasca kerri*), thrips, and pod borer (*Maruca vitrata*) were applied uniformly across all plots whenever scouting indicated treatment thresholds had been reached. All other agronomic operations were carried out according to the standard production recommendations for Kharif mungbean in Punjab.

Data recording

Two response variables were recorded: grain yield and thousand grain weight. Grain yield (kg ha^{-1}). At physiological maturity, the crop was harvested manually from the net plot area, leaving border rows excluded to minimize edge effects. Harvested plants were sun-dried, threshed, and the grain was cleaned, weighed, and adjusted to a standard moisture basis of 12% using a calibrated digital grain moisture meter. Plot-level grain yield was then extrapolated to a per-hectare basis (kg ha^{-1}) at 12% moisture content. Thousand grain weight (TGW, g). Following threshing and moisture adjustment, three random sub-samples of 1,000 grains were drawn from the cleaned grain of each plot using a seed counter and weighed on an electronic precision balance (resolution 0.01 g). The three sub-sample weights were averaged to give a single plot-level TGW value at 12% moisture basis.

Statistical analysis

The data for grain yield and thousand grain weight were each subjected to two-factor combined analysis of variance (ANOVA) appropriate for a multi-location randomized complete block design, with locations and treatments treated as fixed effects and replications nested within locations. Where the location × treatment interaction was significant, simple-effect means were computed for each treatment within each location; where it was non-significant, treatment means were pooled across locations. Treatment means were separated using Fisher's protected least significant difference (LSD) test at the 5% probability level (Steel *et al.*, 1997). The significance of location, treatment, and location × treatment interaction effects was tested at $p \leq 0.05$ and $p \leq 0.01$ levels. The yield response of each fertilization treatment over the unfertilized absolute control was computed for each location as the absolute and percentage difference from T1. Statistical analyses were performed using Statistix 8.1, and graphical presentations were prepared using R/RStudio and Microsoft Excel.

RESULTS AND DISCUSSION

Soil status of the experimental sites

The soil analytical data presented in Table 1 confirmed that the eight experimental sites represented a substantial fertility gradient within the broadly similar alkaline matrix of the Punjab cropping plain. Surface soil pH varied from 7.50 at Faisalabad to 8.30 at Layyah and the three Mianwali sites, conditions that span the upper end of the optimum range for mungbean root activity and progressively constrain the plant availability of several essential cations. Electrical conductivity differentiated the sites sharply, ranging from non-saline at Bhakkar (0.58 dS m^{-1}) and Layyah (0.65 dS m^{-1}) to moderately saline at Bahawalpur (2.60 dS m^{-1}) and Mianwali-2 (2.50 dS m^{-1}). Organic matter content was uniformly low across all eight sites (0.41–1.13%), with Bahawalpur and Bhakkar registering the lowest values (0.41% and 0.42%, respectively). Available phosphorus was uniformly low (5.0–7.5 ppm) across all

sites, and available potassium varied from 124 ppm (deficient, Bhakkar) through 141–190 ppm (low-to-medium, Bahawalpur, Khushab, Mianwali-1/2/3, Faisalabad) to 200 ppm (medium, Layyah). The texture was loam at seven sites and sandy loam at Bhakkar.

The combination of alkaline pH, low organic matter, and moderate salinity at several sites is widely recognized as constraining the availability of K through several interacting mechanisms, including competition with Ca^{2+} and Na^{+} on exchange sites, slow release of non-exchangeable K from the clay interlayer, and reduced K diffusion to root surfaces under elevated soil EC (Rashid and Ryan, 2004; Hawkesford *et al.*, 2012). The site-to-site contrast in soil texture, OM, EC, and available K provided a useful natural fertility gradient against which the consistency of the K response across Punjab could be evaluated.

Analysis of variance

The combined analysis of variance for grain yield and thousand grain weight across the eight locations revealed highly significant effects of all three sources of variation: location, treatment, and their interaction (Table 3). For grain yield, the location main effect (mean square 1,742,016; $p < 0.01$), the treatment main effect (mean square 1,622,289; $p < 0.01$), and the location × treatment interaction (mean square 22,846; $p < 0.01$) were all highly significant. The pattern was directionally identical for thousand grain weight, with location, treatment, and interaction mean squares of 147.842, 116.360, and 2.934 respectively, all significant at $p < 0.01$.

Table 3. Combined analysis of variance (mean squares) for grain yield and thousand grain weight of Kharif mungbean across eight locations and six fertilization treatments.

Source of variation	DF	Grain yield (MS, kg ha^{-1})	Thousand grain weight (MS, g)
Replications (A)	2	4,079	0.429
Locations (B)	7	1,742,016 **	147.842 **
Error A × B	14	3,487	0.505
Treatments (C)	5	1,622,289 **	116.360 **
B × C interaction	35	22,846 **	2.934 **
Error (residual)	80	2,741	0.456
Total	**143**		

*Note: ** = significant at 1% probability level. Grain yield in kg ha^{-1}; TGW in g.*

These ANOVA patterns convey three useful pieces of information. First, the highly significant location effects on both variables confirm that the eight experimental sites produced substantially different absolute yield ceilings, consistent with their contrasting soil fertility status. Second, the highly significant treatment effects on both variables establish that the graded fertilization treatments produced statistically discernible improvements in grain yield and thousand grain weight over the unfertilized control across the eight sites combined. Third, the highly significant location × treatment interactions indicate that the magnitude and, to some extent, the shape of the fertilization response varied between sites.

Grain yield response across sites

The site-wise and pooled mean grain yields of Kharif mungbean under the six fertilization treatments are summarized in Table 4 and depicted in Figures 1–9. The absolute control (T1, no fertilizer) produced a pooled mean grain yield of 841.6 kg ha^{-1} across the eight sites, with site-wise values ranging from 423 kg ha^{-1} at Layyah to 1,188 kg ha^{-1} at Bhakkar. The application of the N+P basal alone (T2; 62.5 kg N + 86 kg P_2O_5 ha^{-1}, no K) raised the pooled mean grain yield to 1,265.6 kg ha^{-1}, an absolute gain of +424.0 kg ha^{-1} (+50.4%) over the unfertilized control, a substantial improvement obtained without any K input. The four NP+K treatments (T3 through T6) produced progressively higher yields, with the pooled mean rising from 1,386.9 kg ha^{-1} at 30 kg K_2O ha^{-1} to 1,545.8 kg ha^{-1} at 60 kg K_2O ha^{-1}. The highest pooled mean grain yield was therefore recorded at T6, representing an absolute gain of +704.1 kg ha^{-1} (+83.7%) over the absolute control and a further +280.1 kg ha^{-1} (+22.1%) over the NP-only baseline.

Table 4. Site-wise and pooled mean grain yield (kg ha^{-1}) of Kharif mungbean (cv. AZRI-Mung 2021) under six fertilization treatments across eight locations of Punjab.

Location	T1 Control	T2 (NP only)	T3 (K_{30})	T4 (K_{40})	T5 (K_{50})	T6 (K_{60})	Gain T6−T1
Faisalabad	527	1100	1303	1372	1383	1417	+890
Bahawalpur	567	963	1074	1296	1375	1441	+874
Layyah	423	561	804	930	1057	1161	+738
Mianwali-1	1074	1663	1709	1741	1793	1807	+733
Mianwali-2	1093	1667	1707	1728	1756	1787	+694
Mianwali-3	1111	1654	1689	1711	1739	1770	+659
Bhakkar	1188	1564	1603	1635	1660	1693	+505
Khushab	750	953	1206	1220	1264	1290	+540
Pooled mean	**841.6**	**1265.6**	**1386.9**	**1454.1**	**1503.4**	**1545.8**	**+704.19**

The yield response curve at the pooled level can be decomposed into two physiologically distinct components. The first and quantitatively dominant component is the response to nitrogen plus phosphorus alone, captured by the T2 − T1 contrast: even in the absence of any K input, the addition of 62.5 kg N + 86 kg P_2O_5 ha^{-1} over the unfertilized control produced a +50.4% pooled-mean yield improvement, consistent with widespread N+P limitation in the unfertilized mungbean crop on Pakistan's alkaline-calcareous soils (Imran *et al.*, 2020). The second component, the response to graded K on top of the NP baseline, is captured by the T6 − T2 contrast, which added a further +22.1% on a pooled-mean basis. Although smaller in relative magnitude than the N+P effect, the K response is agronomically meaningful, particularly because it was obtained on top of an already well-fertilized N+P baseline rather than against a true zero control, and was statistically significant at all eight sites (Table 3, treatment effect $p < 0.01$).

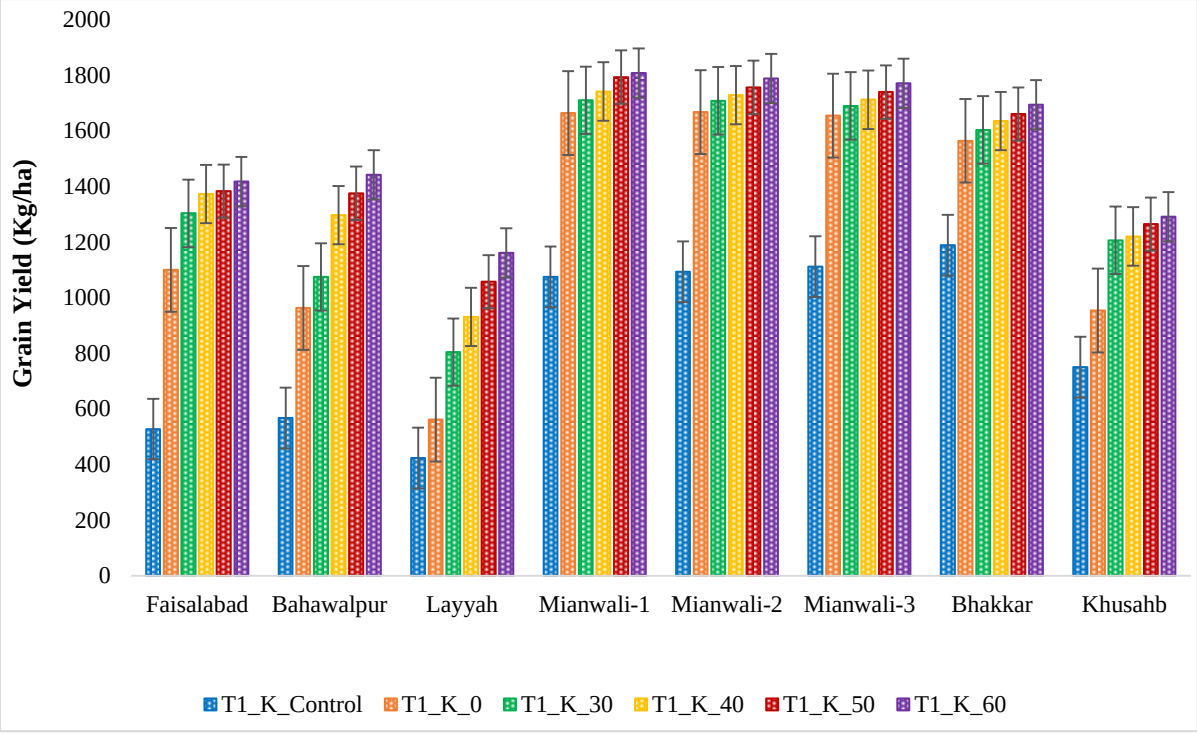

Fig. 1. Performance of mungbean crop at five different potassium fertilization levels at eight different locations.

Physiological basis of the potassium response

The progressive yield improvement under graded K fertilization is consistent with established understanding of potassium nutrition in pulse crops. Potassium is the most abundant cation in plant tissues and is functionally central to stomatal regulation, phloem loading of sucrose and amino acids, enzyme activation, and osmotic adjustment under heat and water stress (Hawkesford *et al.*, 2012; Hasanuzzaman *et al.*, 2018). In nodulating legumes such as mungbean, K supply has additionally been shown to enhance nodule mass and the efficiency of biological nitrogen fixation, to promote translocation of fixed nitrogen and photo-assimilate from source leaves to developing pods, and to extend the effective pod-filling duration under late-season heat stress (Sangakkara *et al.*, 1996; Wang *et al.*, 2013). The combination of these processes accounts for the observed pattern of progressively rising grain yield and thousand grain weight under graded K supply across the eight Punjab sites.

It should be acknowledged that the K supply in the present trial was delivered as sulphate of potash (K_2SO_4), which co-supplied sulphur at approximately 18% S by mass of the SOP applied. At the highest K rate (60 kg K_2O ha^{-1}, corresponding to 120 kg SOP ha^{-1}), the incidental S input was approximately 22 kg S ha^{-1}. Sulphur is itself an essential nutrient for legumes, required for the synthesis of S-containing amino acids (cysteine, methionine), nodule leghaemoglobin, and seed storage proteins, and S deficiency has been shown to specifically depress nodulation, nitrogenase activity, and biological nitrogen fixation efficiency in nodulated legumes (Becana *et al.*, 2018). The yield response observed in the present study is therefore most accurately characterized as a response to K together with co-supplied S, rather than to K in isolation. This co-supply is agronomically advantageous on the soils studied here, where both nutrients are likely to be limiting under continuous unfertilized cropping, and the SOP-based recommendation derived below should be understood in this combined-nutrient context.

Location × treatment interaction and site-level response patterns

The highly significant location × treatment interaction for grain yield (Table 3, $p < 0.01$) reflects substantial variation in the magnitude of the fertilization response across the eight sites, even though the direction of response was uniformly positive (Figures 2–9). Three distinct response patterns can be identified in the site-level data presented in Table 4.

At low- to medium-yielding southern and central Punjab sites, Faisalabad, Bahawalpur, Layyah, and Khushab, the absolute control produced very low yields (423–750 kg ha^{-1}), reflecting strong limitation by the absence of any fertilizer input. The NP basal alone delivered substantial yield gains at these sites (+203 to +573 kg ha^{-1} over T1), and the K response on top of NP added a further +203 to +600 kg ha^{-1} from T2 to T6. Layyah in particular showed an essentially linear yield response across the entire K series (T2 = 561; T3 = 804; T4 = 930; T5 = 1,057; T6 = 1,161 kg ha^{-1}), with no evidence of approaching a plateau even at 60 kg K_2O ha^{-1}. This pattern indicates that mungbean grown on Layyah-type Thal soils, despite their apparent K sufficiency on the basis of standard soil-test values (200 ppm available K), shows a strong agronomic response to additional K supply, a finding consistent with the well-recognized limitation of single-extractant soil-K tests as predictors of crop response under field conditions (Hawkesford *et al.*, 2012).

At the three Mianwali sites, Mianwali-1, Mianwali-2, and Mianwali-3, the absolute control produced relatively high yields (1,074–1,111 kg ha^{-1}), and the response to the NP basal alone was particularly large (+543 to +589 kg ha^{-1} from T1 to T2). The further K response on top of NP, however, was modest (+116 to +144 kg ha^{-1} from T2 to T6), with the yield curve flattening progressively beyond the 30 kg K_2O ha^{-1} rate. This plateau-like pattern indicates that the Mianwali sites carry adequate K reserves to meet the demand of the moderately yielding mungbean crop, but that NP supply remains the dominant nutritional constraint.

Bhakkar represented an intermediate pattern: the absolute control yield was the highest of any site (1,188 kg ha^{-1}), the NP response was substantial (+376 kg ha^{-1}), and the K response was modest but consistent (+129 kg ha^{-1} from T2 to T6). Notably, Bhakkar had the lowest available soil K of any site (124 ppm) yet showed the smallest K response, while Layyah had the highest available soil K (200 ppm) yet showed the largest K response. This inverse relationship between soil-test K and field K response, a pattern frequently observed in long-term multi-location trials (Yin *et al.*, 2018), underscores the limitations of single-point soil-K extractants as predictors of agronomic response and argues for empirical multi-location calibration of K recommendations rather than reliance on soil-test thresholds alone.

Despite this site-level variability, two important consistencies emerged from the disaggregated data. First, the direction of the response was uniformly positive at every site, with no instance of a yield depression under any fertilization treatment. Second, the highest yield at every one of the eight sites was recorded at T6 (60 kg K_2O ha^{-1}), with no site showing a plateau or decline at the highest tested K rate. These two consistencies support the use of a single regional K recommendation despite the formally significant location × treatment interaction.

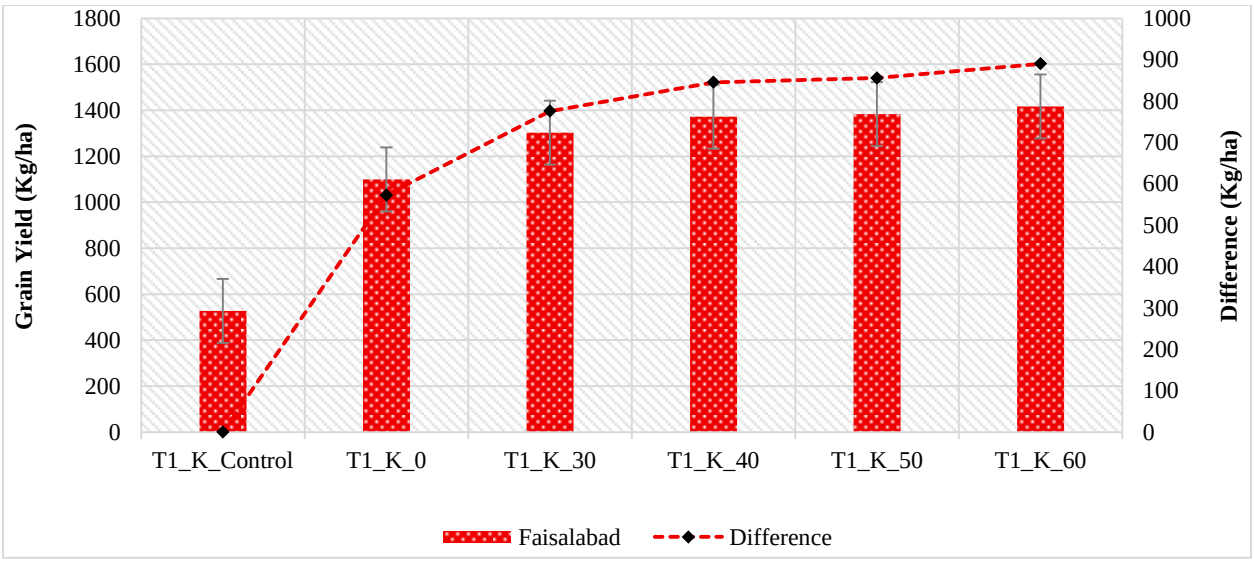

Fig. 2. Yield performance of mungbean crop at five different potassium fertilization levels at Faisalabad location and yield difference from control.

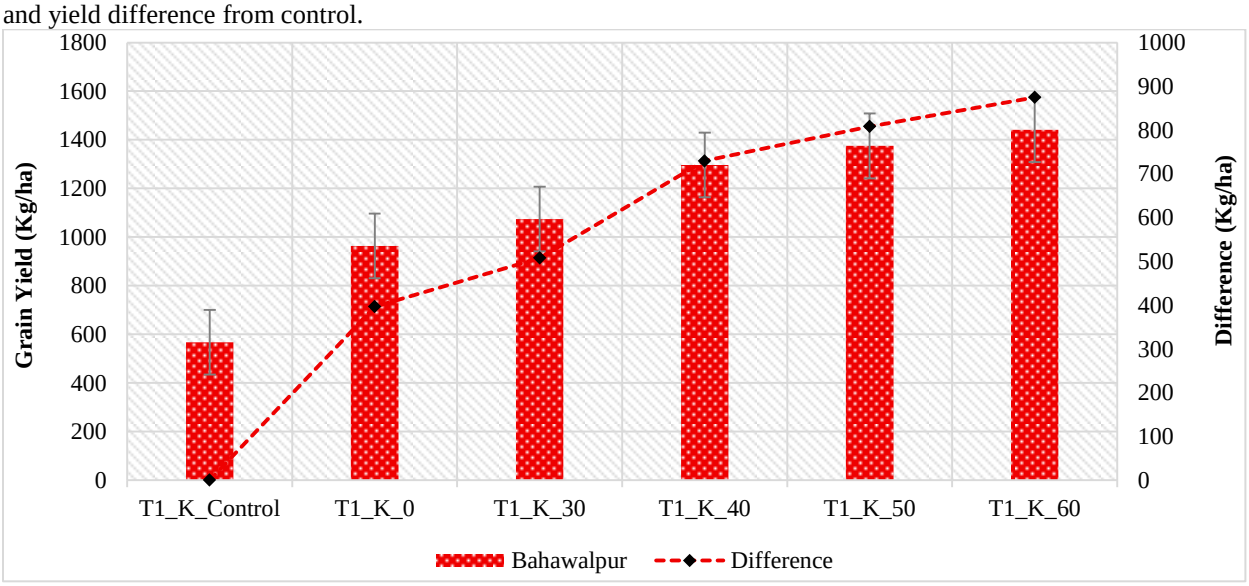

Fig. 3. Yield performance of mungbean crop at five different potassium fertilization levels at Bahawalpur location and yield difference from control.

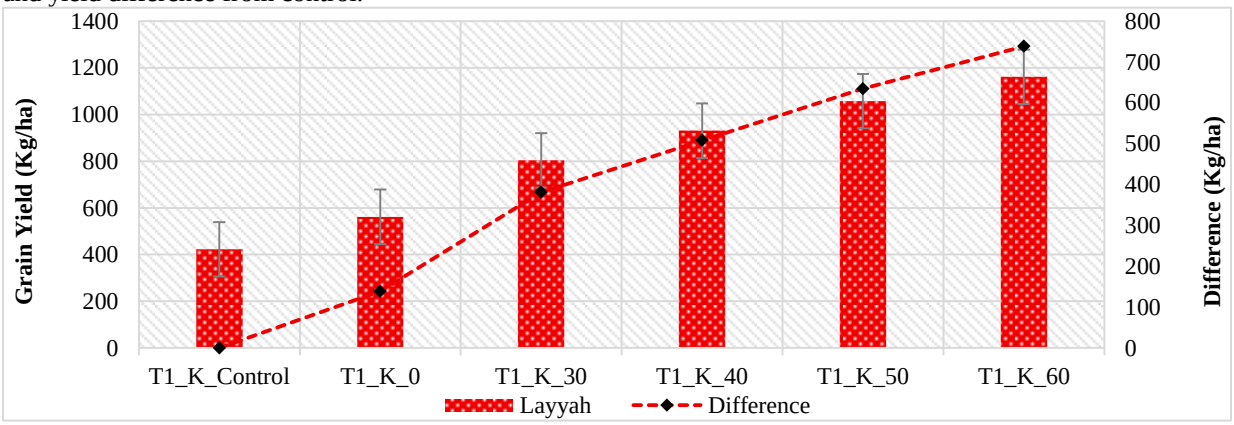

Fig. 4. Yield performance of mungbean crop at five different potassium fertilization levels at Layyah location and yield difference from control.

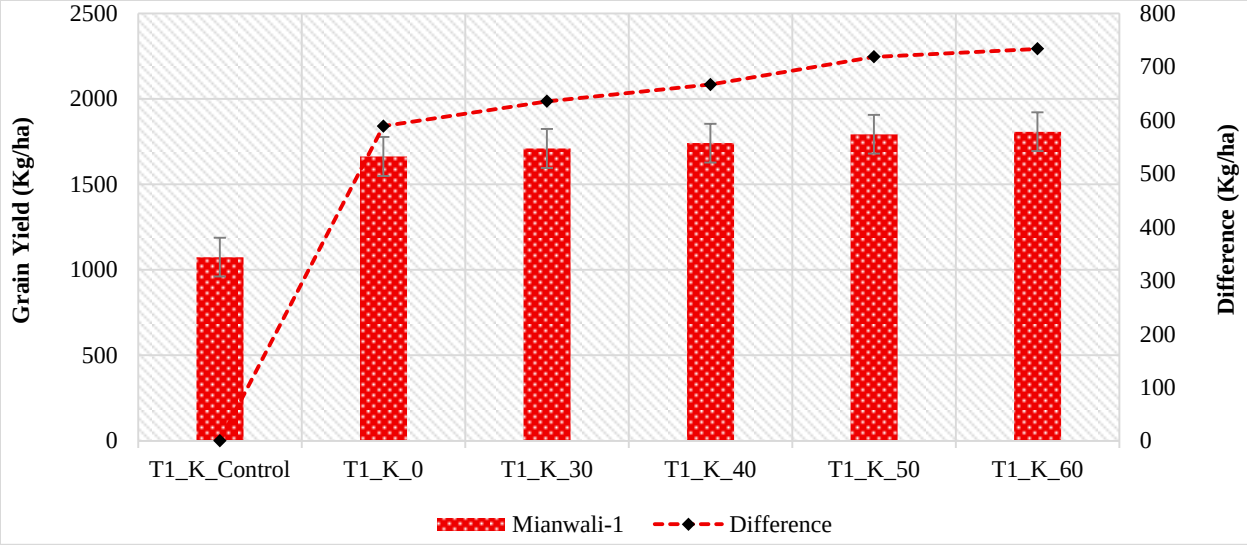

Fig. 5. Yield performance of mungbean crop at five different potassium fertilization levels at Mianwali-1 location and yield difference from control.

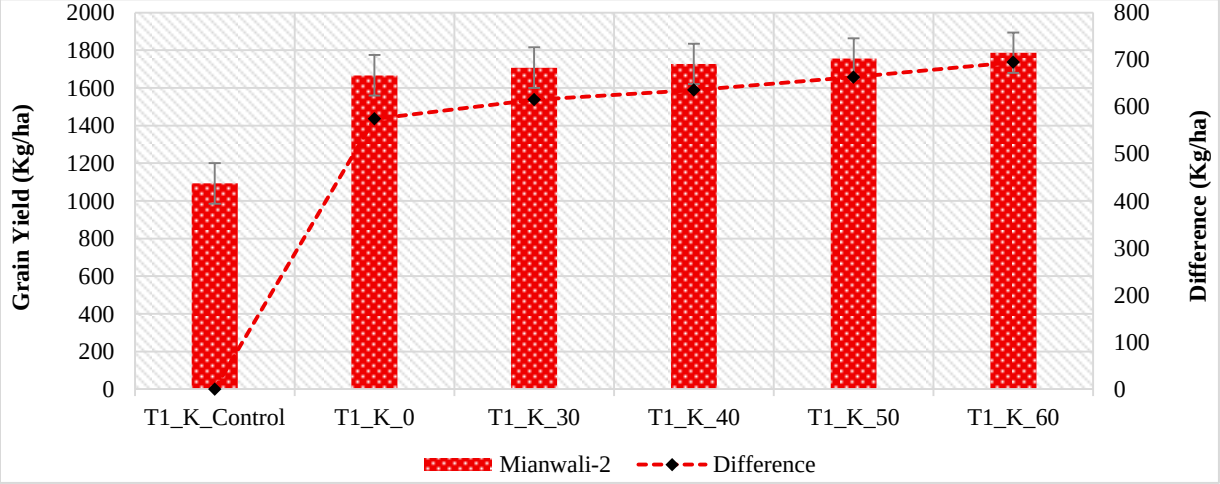

Fig. 6. Yield performance of mungbean crop at five different potassium fertilization levels at Mianwali-2 location and yield difference from control.

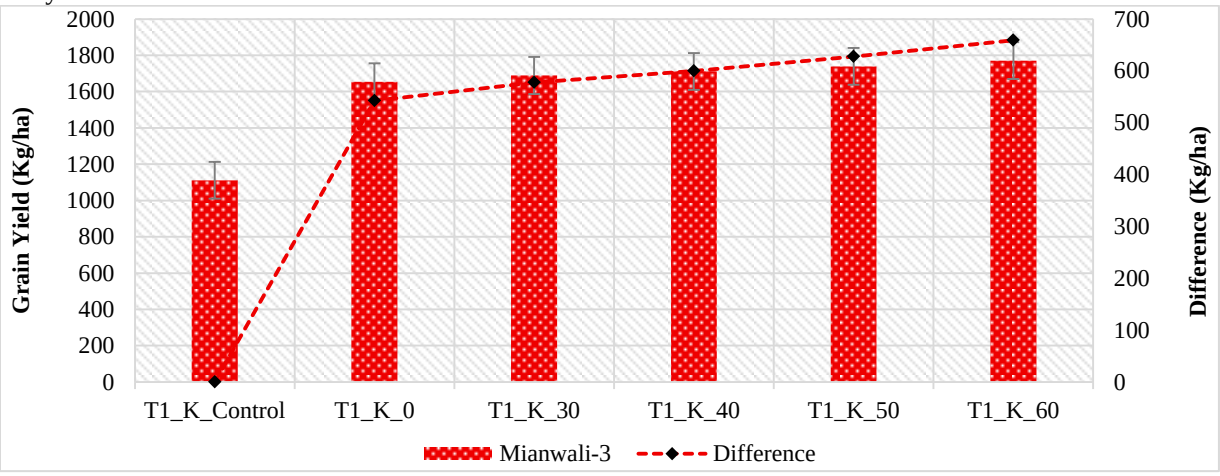

Fig. 7. Yield performance of mungbean crop at five different potassium fertilization levels at Mianwali-3 location and yield difference from control.

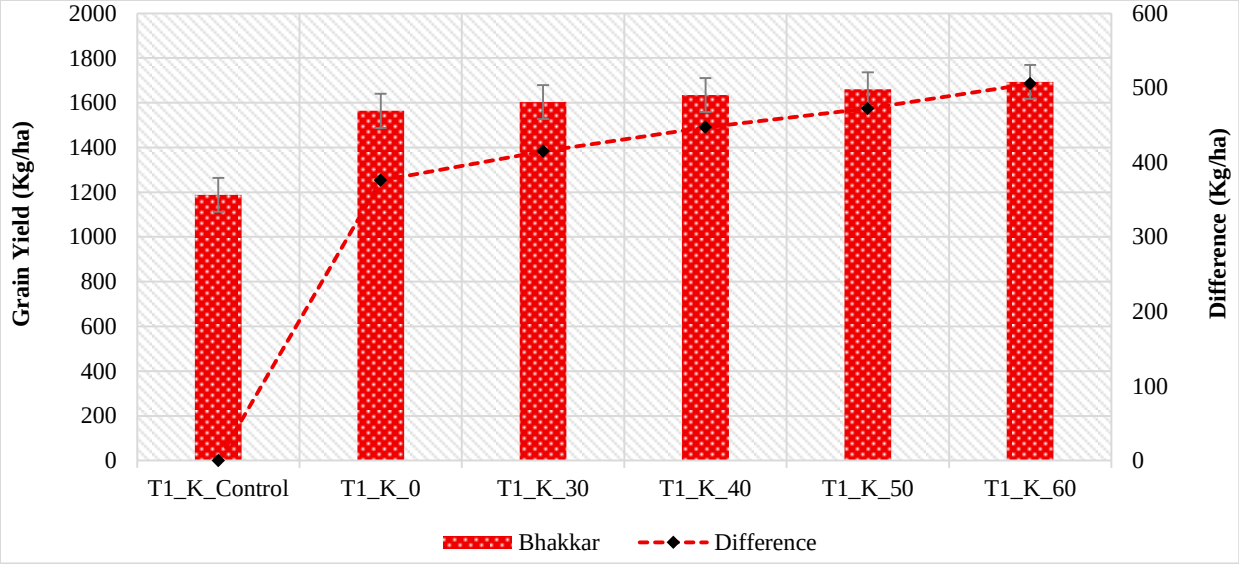

Fig. 8. Yield performance of mungbean crop at five different potassium fertilization levels at Bhakkar location and yield difference from control.

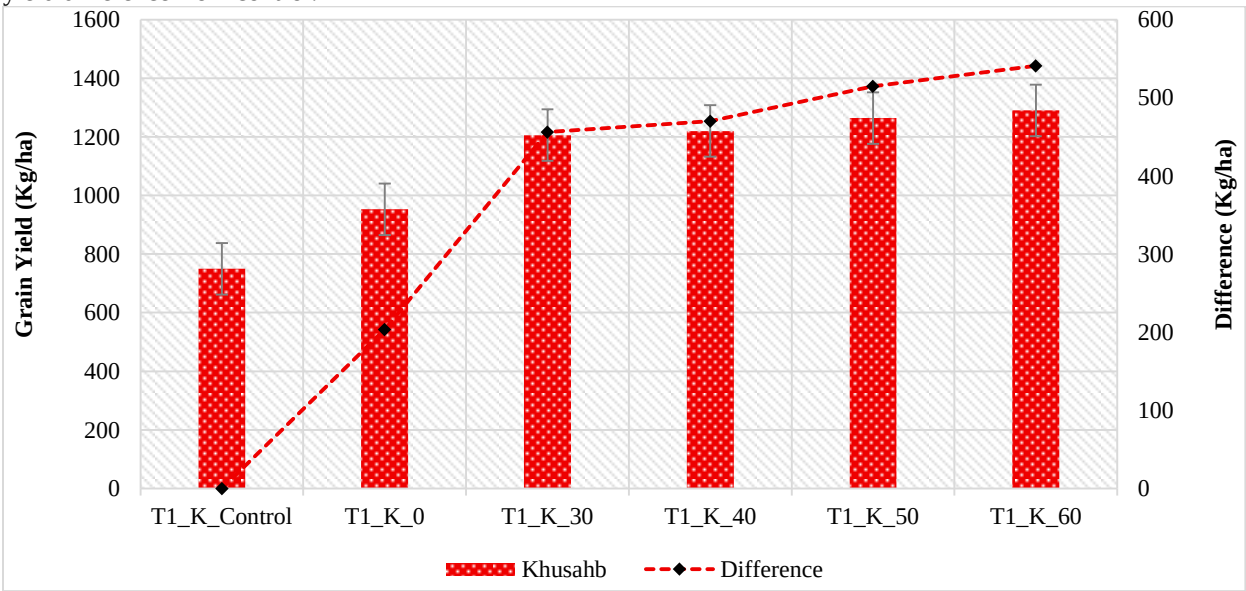

Fig. 9. Yield performance of mungbean crop at five different potassium fertilization levels at Khushab location and yield difference from control.

Identifying the recommended K rate

Taking the pooled and location-wise yield responses together, the T6 treatment (62.5 kg N + 86 kg P_2O_5 + 60 kg K_2O ha^{-1}) produced the largest absolute grain yield response over the unfertilized control in both the pooled-mean analysis and the site-level disaggregation, and is therefore identified as the recommended fertilization regime for Kharif mungbean (cv. AZRI-Mung 2021) on the alkaline-calcareous soils of Punjab. At this rate, the pooled mean grain yield reached 1,545.8 kg ha^{-1}, representing an absolute gain of +704.1 kg ha^{-1} (+83.7%) over the absolute control, and an additional +280.1 kg ha^{-1} (+22.1%) over the NP-only baseline. The site-wise yield gain at T6 over the absolute control ranged from +505 kg ha^{-1} at Bhakkar to +890 kg ha^{-1} at Faisalabad, indicating that the recommendation is robust to substantial variation in baseline soil fertility, salinity, and texture across Punjab.

Because the yield response curves were still rising at the highest tested K rate at every site, with no evidence of a plateau, the true sufficiency threshold for soil-applied K on these soils may lie at or beyond 60 kg K_2O ha^{-1}. Future work should therefore evaluate higher K rates (e.g., 75 and 90 kg K_2O ha^{-1}) to identify the upper limit of the agronomic response, particularly at the highly responsive southern and central Punjab sites such as Layyah,

Faisalabad, and Bahawalpur. For current extension purposes, however, the inclusion of 60 kg K_2O ha^{-1} (supplied as approximately 120 kg SOP ha^{-1}) as a basal soil-applied input, alongside the standard NP basal of 62.5 kg N + 86 kg P_2O_5 ha^{-1}, emerges as the agronomically defensible recommendation supported by the present multi-location data.

Conclusion

This eight-location field investigation (Soil Fertility Punjab project PLAN-10, Kharif 2024) demonstrated that soil-applied potassium significantly improved the grain yield of Kharif mungbean (cv. AZRI-Mung 2021) on alkaline-calcareous Punjab soils, beyond the response already obtained from a uniform N+P basal. Pooled across eight sites, yield rose from 841.6 kg ha^{-1} at the absolute control to 1,265.6 kg ha^{-1} at the NP basal (+50.4%) and to 1,545.8 kg ha^{-1} at the highest K rate (+83.7% over control; +22.1% over NP), peaking at 60 kg K_2O ha^{-1} at every site with no plateau. Although the K response varied in magnitude across sites (strongest at Layyah, Faisalabad, and Bahawalpur), its direction was uniformly positive. Accordingly, 60 kg K_2O ha^{-1} (≈120 kg sulphate of potash ha^{-1}), applied basally alongside 62.5 kg N + 86 kg P_2O_5 ha^{-1}, is recommended for Kharif mungbean across canal-irrigated Punjab. As the response was still rising at the highest rate, future work should test higher K rates, co-supplied sulphur, alternative seasons and varieties, and grain quality parameters to develop a fully integrated fertilizer recommendation.

Author contributions

MJQ: Conceptualization and execution, supervision, planning, writing – original draft. ZC, NR, GY, AHM: Experimental layout, field execution and crop management at the Faisalabad-zone sites and overall trial coordination. MRF: Experimental layout and field execution at the Bahawalpur trial node. AGK: Project oversight, statistical analysis, writing – review and editing. AK, WE: Field execution at the southern Punjab trial nodes. MK: Field execution and soil sampling at the Bhakkar site. MA: Soil chemical analysis, soil fertility characterization. MR: Field execution at the Pothwar–Thal margin trial node, data compilation. MJQ, AGK, ZC: Writing – review and editing.

Conflict of interest

The authors declared absence of conflict of interest.

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