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Nitrogen rate governs soil nutrient availability and grain yield of white common bean (Phaseolus vulgaris L.) double-cropped after winter wheat on irrigated light sierozem soils of the Fergana Valley, Uzbekistan

Isakov V.Yu. [1], **Iminchaev R.** [2, *]
[1] DSc, Professor, Kokand State University, 23 Turon Street, 150101 Kokand, Uzbekistan
; e-mail: valijonisaqov247@gmail.com;
ORCID: 0009-0009-6095-1768
[2] Doctoral student, Fergana State University, 19 Murabbiylar Street, 150100 Fergana, Uzbekistan;
e-mail: iminchayevraxmatjon@gmail.com;
ORCID: 0009-0006-2720-6473
* Corresponding author: iminchayevraxmatjon@gmail.com
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Abstract: Purpose. Common bean is a weak nitrogen fixer among the grain legumes and is therefore expected to respond differently to mineral nitrogen than the crops it is usually grouped with. This study quantified how the rate and balance of mineral fertilisers govern the seasonal dynamics of plant-available soil nutrients, soil microbial abundance and the grain yield of white common bean grown as a repeat crop after winter wheat on irrigated stony-gravelly light sierozem soil.

Methods. A three-year field experiment (2022–2024) was conducted in the Fergana Valley, Uzbekistan. Five treatments — an unfertilised control, P60K40, N20P80K60, N20P40K20 and N40P60K40 kg ha^{-1} — were arranged in a randomised complete block design with three replications (plot area 240 m^2). Ammonium and nitrate nitrogen, available phosphorus and exchangeable potassium were determined in the 0–30 cm layer at eight dates per season; microbial groups were enumerated before sowing and after harvest; grain yield was recorded per replication. Randomised-block analysis of variance with $LSD_{0.05}$ was applied.

Results. All soil indicators responded significantly to fertilisation (F = 9.2–585.1; S_x = 0.17–1.84 %). Unlike mung bean grown in the same experiment, common bean responded positively up to the highest nitrogen rate tested: N40P60K40 gave the highest season-mean mineral nitrogen (38.98 vs 29.35 mg kg^{-1} in the control), the highest exchangeable potassium (255 mg kg^{-1}) and the highest grain yield (1.81 t ha^{-1}, +1.06 t ha^{-1} or +141 % over the control; $LSD_{0.05}$ = 0.046 t ha^{-1}). Available phosphorus reached a plateau at 28.45–28.41 mg kg^{-1} and did not increase further when the phosphorus rate was doubled. The repeat crop raised the abundance of all microbial groups two- to more than three-fold. Season-mean available phosphorus predicted grain yield almost perfectly (r = 0.993; R^2 = 0.986; P = 0.001).

Conclusion. On this soil, white common bean grown as a repeat crop after winter wheat requires N40P60K40 kg ha^{-1} for maximum yield, while phosphorus above 60 kg P_2O_5 ha^{-1} brings no further benefit. The contrast with mung bean grown in the same experiment shows that a single fertiliser recommendation cannot be applied to grain legumes as a group.

Keywords: Phaseolus vulgaris; double cropping; light sierozem; nitrogen rate; available phosphorus; soil microbial abundance; least significant difference; Fergana Valley.

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1. Introduction

Common bean is the most widely consumed grain legume in the world and a traditional food crop of Central Asia, where white-seeded types are used in soups and porridges. Compared with other grain legumes it is a comparatively weak symbiotic nitrogen fixer, and its yield responds strongly to applied nutrients: phosphorus and potassium fertilisation raised grain yield in African savanna soils to as much as 3.6 t ha^{-1} with an estimated optimum near 239 kg P_2O_5 and 141 kg K_2O ha^{-1} [1], potassium rates up to 40 kg K_2O ha^{-1} significantly improved yield components in Ethiopia [2], and phosphorus rates of 60–80 kg P_2O_5 ha^{-1} improved yield in Afghanistan and in phosphorus-fixing Luvisols [17, 19]. Because its symbiosis is comparatively inefficient, common bean sustains its yield only when either rhizobial inoculation or mineral nitrogen supplements biological fixation [21, 20].

In the irrigated arid lands of Central Asia, grain legumes are of interest mainly as repeat crops. The dominant rotation is winter wheat–cotton, and water rather than land limits production [4, 3]. Sowing a legume on the area released by winter wheat in early July yields a second grain crop in the same year and leaves a nitrogen-rich residue for the following crop. Uzbek studies of the irrigated sierozem and meadow-alluvial zones report that balanced mineral–organic fertilisation outperforms high mineral inputs alone [6, 7]; conservation rotations that place legumes between cereals raise soil N, P, K and humus [5].

The legacy of a legume extends beyond its own grain. Legume-based diversification improves the yield, nitrogen nutrition and yield stability of the following cereal, and raises soil quality indices, with the largest relative effects at low nitrogen input [9, 10]; summer legumes after winter wheat can more than double soil nitrate availability and deliver apparent nitrogen credits of tens of kilograms per hectare [11]. Much of this legacy is biological. Cover crops increase microbial biomass carbon and nitrogen by 40 % and 51 % respectively [12]; legume-based rotations raise bacterial numbers, enzyme activities and the abundance of nitrogen-cycling genes [13, 14, 16]; and the effect is driven by residue quality, since nitrogen-rich, easily decomposable legume residues select for rapid decomposers [15].

How much fertiliser a repeat common bean crop needs on a calcareous, coarse-textured soil is not known. Integrated fertilisation studies show that phosphorus response in common bean is strongly site-specific, and that on phosphorus-fixing soils a substantial part of the applied phosphorus never reaches the labile pool [18, 19]. Irrigated serozems of Uzbekistan are precisely such soils: 89–91 % of their phosphorus is inorganic and strongly fixed, and the labile fraction depends more on land use and moisture than on the amount applied [8]. At the same time, mineral nitrogen is known to suppress the legume–rhizobium symbiosis by blocking iron delivery to nodules [22] and by reducing nodule number and nitrogenase activity above modest thresholds [23, 24] — an effect that an adequate phosphorus supply partly offsets [25]. Whether a weak fixer such as common bean is limited by this trade-off in the same way as a strong fixer is an open question of direct practical importance.

The objectives of this study were therefore (i) to quantify the effect of four contrasting NPK rates on the seasonal dynamics of ammonium and nitrate nitrogen, available phosphorus and exchangeable potassium in the ploughed layer under a repeat white common bean crop; (ii) to describe the change in the abundance of the main groups of soil microorganisms associated with the crop; (iii) to determine which rate maximises grain yield with statistically defensible precision; and (iv) to test how well soil nutrient status predicts yield. Because common bean fixes nitrogen less effectively than mung bean, we hypothesised that, in contrast to mung bean grown in the same experiment, its yield would continue to increase up to the highest nitrogen rate tested.

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2. Materials and methods

2.1. Study site and soil

The field experiment was carried out in 2022, 2023 and 2024 on the irrigated stony-gravelly light sierozem soils of the "Iqbol mirzo zamini" farm, Fergana district, Fergana region, in the north-western part of the Fergana Valley, Uzbekistan. The site belongs to the Fergana agroclimatic district, which is classified as a hot zone: the annual sum of effective air temperatures is about 2500 °C, the frost-free period lasts 200–227 days, mean annual precipitation is 172–198 mm and falls mostly in winter and spring, and mean relative air humidity is 58–60 % annually and 62–64 % during the growing season. Crop production therefore depends entirely on irrigation.

Before the experiment, the ploughed layer (0–30 cm) of the experimental field contained 0.83–1.39 % humus, with a C:N ratio of 6.1–9.5, 0.060–0.085 % total nitrogen, 0.182–0.200 % total phosphorus and 0.49–0.90 % total potassium. Bulk density was 1.25–1.30 g cm^{-3} and total porosity 52–53 %. The exchange complex was dominated by calcium (74.9 % of the sum of exchangeable bases) and magnesium (17.5 %), with a sum of exchangeable bases of about 10.1 cmol(+) kg^{-1}. According to the regional soil survey, 84 % of the soils of Fergana district are non-eroded and 51 % are of medium loamy texture. Soils of this type are rich in total phosphorus but supply plant-available phosphorus poorly because of strong phosphate fixation in the carbonate-rich matrix [8].

2.2. Experimental design and crop management

The preceding crop in all three years was winter wheat, harvested in the first days of July. White common bean (Phaseolus vulgaris L.) was then sown as a repeat (second) crop on the released area. The experiment comprised five treatments (Table 1) arranged in a randomised complete block design with three replications, in two tiers, giving 30 plots in total. Each plot measured 4.8 × 50 m (240 m^2), of which 120 m^2 was the harvested area; each plot contained eight rows, of which the two outer rows on each side served as borders and the four central rows were harvested. The area of one replication was 2400 m^2 and the total experimental area 7200 m^2.

A locally grown white-seeded common bean population was used (growing period 75–120 days; taproot reaching 1.5–2.0 m with the main root mass in the upper 40 cm; 6–12 seeds per pod; seed protein content 20–31 %).

Crop management followed the technology adopted on the farm and was identical in all three years. After the wheat harvest the field was irrigated with 500–600 m^3 ha^{-1} before ploughing, ploughed with a PN-4-35 plough to 28–30 cm on 5–6 July, harrowed and rolled on 7–8 July, and sown on 8–12 July, followed by a germination irrigation. Nitrogen fertiliser was applied in three equal splits: at the two- to three-true-leaf stage, at budding and at the beginning of flowering. Half of the phosphorus was applied under the plough and the remaining half was split between pre-sowing application and the flowering stage; half of the potassium was applied under the plough and the remaining half was split between pre-sowing application and budding.

2.3. Soil sampling and analyses

Composite soil samples were taken from the 0–30 cm layer of every plot at eight dates during each growing season — on 5 and 20 July, 5 and 20 August, 5 and 20 September, and 5 and 20 October — that is, every 15 days from sowing to the end of the vegetation period. Ammonium nitrogen was determined colorimetrically with Nessler reagent, nitrate nitrogen by the Grandval–Lyazhu method, available phosphorus (P_2O_5) by the Machigin method and exchangeable potassium (K_2O) by flame photometry after Machigin–Protasov. Humus was determined by the Tyurin method, total N, P and K

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from a single digest by the Maltsev–Grisenko method, soil reaction potentiometrically, bulk density by the core method and particle-size distribution by the Kachinskiy pipette method. All procedures followed the regional methodological guides for agrochemical, agrophysical and microbiological research in irrigated cotton-growing areas [26].

Soil microbiological composition was determined in 2024 in the 0–30 and 30–50 cm layers, immediately before sowing the repeat crop and immediately after its harvest. Bacteria were counted on meat–peptone agar, fungi on Czapek medium, actinomycetes on starch–ammonia agar, free-living nitrogen-fixing bacteria on Ashby medium, nitrifiers on Vinogradsky medium, denitrifiers on Giltay medium and cellulolytic microorganisms on Hutchinson medium.

2.4. Statistical analysis

Grain yield was recorded separately for the three field replications of each treatment in each year. Soil chemical data are reported as means of the three experimental years. Analysis of variance was performed following the randomised-block model of Dospekhov [27]. For the soil indicators the three experimental years were treated as blocks (v = 5 treatments, n = 3 blocks, error df = 8) and a separate analysis was run for each sampling date and for the season mean. For grain yield the analysis was run within each year on the three field replications (v = 5, n = 3, error df = 8); the three-year least significant difference was computed from the error mean square pooled over years (df = 24) for n = 9 observations per treatment.

The following statistics are reported: the Fisher variance ratio (F) with its 5 % critical value $F_{0.05}(4; 8) = 3.84$, the index of experimental precision S_x (%), and the least significant difference $LSD_{0.05} = t_{0.05} \times \sqrt{(2 \times MS_{error} / n)}$. A difference from the control was regarded as significant when its absolute value equalled or exceeded $LSD_{0.05}$ ($P < 0.05$) and is marked with an asterisk in the tables; non-significant differences are marked "ns". Relationships between fertiliser rates, soil nutrient status and grain yield were examined by Pearson correlation and linear regression on treatment means (n = 5); at this sample size only $|r| \geq 0.878$ is significant at $P < 0.05$. Computations were verified independently in two software environments.

Table 1. Treatments of the field experiment and annual fertiliser rates

Treatment	Annual rate, kg ha^{-1}			Total NPK, kg ha^{-1}	Role in the design
	N	P_2O_5	K_2O		
T1 — control (no fertilizer)	0	0	0	0	Unfertilized reference
T2 — P60K40	0	60	40	100	N-free P–K background
T3 — N20P80K60	20	80	60	160	Low N on a high P–K background
T4 — N20P40K20	20	40	20	80	Balanced low rate
T5 — N40P60K40	40	60	40	140	High N with moderate P and K

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3. Results

3.1. Mineral nitrogen

Averaged over three years and eight sampling dates, the unfertilised control contained 19.74 mg kg^{-1} ammonium nitrogen and 9.61 mg kg^{-1} nitrate nitrogen, giving 29.35 mg kg^{-1} of mineral nitrogen (Table 2) — well below the 60 mg kg^{-1} regarded in the region as adequate supply.

The two nitrogen forms behaved differently. Ammonium nitrogen responded only weakly to fertilisation ($F = 9.2$; $LSD_{0.05} = 1.26$ mg kg^{-1}): the increase over the control was significant only in N40P60K40 (+3.02 mg kg^{-1}) and N20P40K20 (+1.63), while N20P80K60 (+0.41) did not differ significantly from the control. Nitrate nitrogen, by contrast, responded strongly and consistently ($F = 348.6$; $LSD_{0.05} = 0.53$ mg kg^{-1}), rising from 9.61 mg kg^{-1} in the control to 16.22 mg kg^{-1} under N40P60K40.

For mineral nitrogen as a whole the ranking followed the nitrogen rate directly: N40P60K40 > N20P40K20 > N20P80K60 > P60K40 > control, with the highest treatment exceeding the control by 9.63 mg kg^{-1} ($LSD_{0.05} = 1.41$). The same ordering held at the end of the vegetation period, when mineral nitrogen under N40P60K40 was 34.77 mg kg^{-1} against 21.73 mg kg^{-1} in the control.

Table 2. Effect of mineral fertiliser rates on ammonium, nitrate and mineral nitrogen in the 0–30 cm layer under a repeat common bean crop (means of 2022–2024)

Treatment	NH_4–N, mg kg^{-1}		NO_3–N, mg kg^{-1}		Mineral N (N_{min}), mg kg^{-1}		
	season mean	20 Oct	season mean	20 Oct	season mean	vs control, ±	sig.
T1 — control (no fertilizer)	19.74	14.57	9.61	7.17	29.35	—	—
T2 — P60K40	21.12	17.43	10.62	8.27	31.74	+2.39	*
T3 — N20P80K60	20.15	18.60	15.63	10.00	35.79	+6.44	*
T4 — N20P40K20	21.37	19.63	14.85	10.07	36.22	+6.87	*
T5 — N40P60K40	22.76	21.77	16.22	13.00	38.98	+9.63	*
$LSD_{0.05}$	1.26	2.33	0.53	0.62	1.41	—	—
S_x, %	1.84	—	1.22	—	1.26	—	—
F value ($F_{0.05} = 3.84$)	9.2	—	348.6	—	78.8	—	—

Note: season mean is the mean of eight sampling dates; "sig." refers to the difference in mineral nitrogen from the control tested against $LSD_{0.05}$; * — significant at $P < 0.05$; ns — not significant.

3.2. Available phosphorus

Available phosphorus rose from 24.64 mg kg^{-1} in the control to 27.17–28.45 mg kg^{-1} in the fertilised treatments, every difference being significant ($LSD_{0.05} = 0.45$ mg kg^{-1}; $F = 139.1$). The response was, however, clearly saturating: N20P80K60, N20P40K20 and N40P60K40 differed from each other by no more than 0.12 mg kg^{-1} — within $LSD_{0.05}$ — even though their phosphorus rates ranged from 40 to 80 kg P_2O_5 ha^{-1} (Table 3).

At the end of the season the ordering was different: available phosphorus on 20 October increased steadily with the nitrogen rate, from 17.00 mg kg^{-1} in the control to 23.40 mg kg^{-1} under

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N40P60K40. A well-nourished crop therefore left the ploughed layer better supplied with phosphorus at the end of the season, even though the mid-season pool was already saturated.

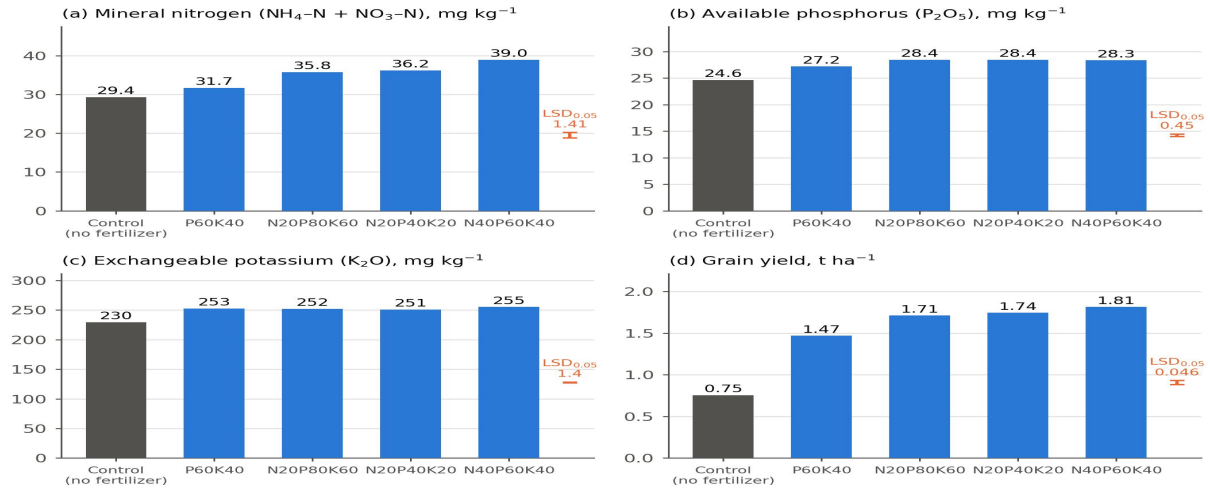
3.3. Exchangeable potassium

Exchangeable potassium was the most precisely determined indicator (S_x = 0.17 %; F = 585.1). The control averaged 230 mg kg^{-1} and the fertilised treatments 251–255 mg kg^{-1}, the highest value again occurring under N40P60K40. As with mung bean grown in the same experiment, exchangeable potassium did not decline over the season in any treatment: values on 20 October equalled or exceeded those on 5 July, the increase ranging from 2 to 13 mg kg^{-1}.

Table 3. Effect of mineral fertiliser rates on available phosphorus and exchangeable potassium in the 0–30 cm layer under a repeat common bean crop (means of 2022–2024)

Treatment	Available P_2O_5, mg kg^{-1}			Exchangeable K_2O, mg kg^{-1}		
	season mean	20 Oct	vs control, ±	season mean	20 Oct	vs control, ±
T1 — control (no fertilizer)	24.64	17.00	—	229.54	203.00	—
T2 — P60K40	27.17	19.27	+2.53 *	252.58	223.67	+23.04 *
T3 — N20P80K60	28.45	22.20	+3.81 *	251.88	231.67	+22.34 *
T4 — N20P40K20	28.41	22.57	+3.77 *	250.92	225.33	+21.38 *
T5 — N40P60K40	28.33	23.40	+3.69 *	255.17	242.00	+25.63 *
$LSD_{0.05}$	0.45	1.82	—	1.41	1.91	—
S_x, %	0.51	—	—	0.17	—	—
F value ($F_{0.05}$ = 3.84)	139.1	—	—	585.1	—	—

Note: differences from the control are followed by the significance verdict against $LSD_{0.05}$; * — significant at $P < 0.05$; ns — not significant.



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Fig. 1. Effect of mineral fertiliser rates on (a) mineral nitrogen, (b) available phosphorus, (c) exchangeable potassium in the 0–30 cm layer (season means of 2022–2024) and (d) grain yield of repeat common bean. The orange bar on the right of each panel is the $LSD_{0.05}$ interval for that indicator.

3.4. Soil microbial abundance

Before the repeat crop was sown, the plots did not differ appreciably in the abundance of any microbial group, and all groups declined with depth (Table 4). After harvest, bacterial numbers in the 0–30 cm layer of the fertilised plots had risen from 34.0–34.9 to 76.0–76.9 million per gram, free-living nitrogen fixers from 24.0–24.9 to 78.2–78.9 million per gram, nitrifiers from 49.0–49.9 to 86.0–86.9 thousand per gram, fungi from 37.0–37.9 to 68.0–68.7 thousand per gram and actinomycetes from 30.0–30.9 to 58.4–58.9 million per gram. The unfertilised control that carried a repeat crop showed the same direction of change at a slightly lower level, while differences among the fertilised treatments were small.

Table 4. Number of the main microbial groups in the soil before sowing and after harvesting the repeat common bean crop, 2024

Treatment	Layer, cm	Bacteria, 10^6 g^{-1}	Free-living N-fixers, 10^6 g^{-1}	Nitrifiers, 10^3 g^{-1}	Fungi, 10^3 g^{-1}	Actinomycetes, 10^6 g^{-1}
Before sowing the repeat crop						
T1	0–30	32.4	23.6	47.0	35.3	29.1
T1	30–50	22.1	14.3	36.8	24.1	17.9
T2	0–30	34.0	24.8	49.4	37.1	30.6
T2	30–50	23.2	15.0	38.6	25.3	18.8
T3	0–30	34.4	24.1	49.7	37.0	30.7
T3	30–50	23.6	15.3	38.8	25.2	18.7
T4	0–30	34.7	24.0	49.0	37.1	30.0
T4	30–50	23.0	15.2	38.0	25.2	18.1
T5	0–30	34.9	24.9	49.9	37.9	30.9
T5	30–50	23.8	15.8	38.8	25.7	18.8
After harvesting the repeat crop						
T1	0–30	72.6	74.8	81.9	65.0	55.8
T1	30–50	51.5	42.8	59.0	51.8	36.5
T2	0–30	76.2	78.5	86.0	68.2	58.6
T2	30–50	54.1	44.9	62.0	54.4	38.3
T3	0–30	76.0	78.2	86.1	68.2	58.4
T3	30–50	54.1	44.4	62.0	54.4	38.5
T4	0–30	76.3	78.4	86.1	68.0	58.7

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Treatment	Layer, cm	Bacteria, 10^6 g^{-1}	Free-living N-fixers, 10^6 g^{-1}	Nitrifiers, 10^3 g^{-1}	Fungi, 10^3 g^{-1}	Actinomycetes, 10^6 g^{-1}
T4	30–50	54.0	44.2	62.2	54.2	38.2
T5	0–30	76.9	78.9	86.9	68.7	58.9
T5	30–50	54.8	44.8	62.7	54.8	38.8

Note: single determination per treatment and layer; no replication was available, so these data are descriptive and were not subjected to analysis of variance.

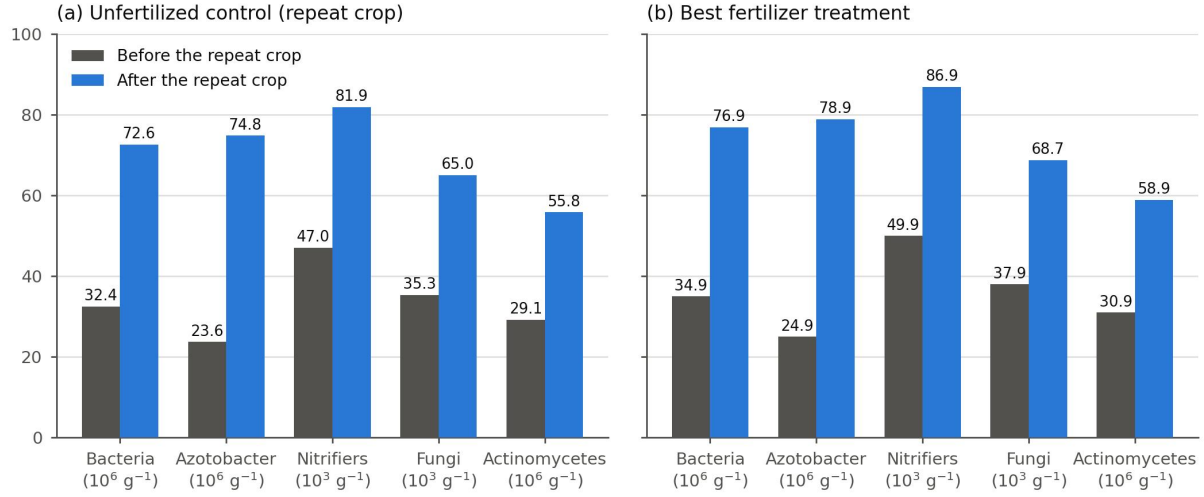


Fig. 2. Abundance of the main microbial groups in the 0–30 cm layer before and after the repeat crop: (a) the unfertilised control, which also carried repeat common bean, (b) the best fertiliser treatment (N40P60K40), 2024.

3.5. Grain yield

Grain yield responded strongly to fertilisation and, unlike mung bean, increased monotonically with the nitrogen rate (Table 5). The unfertilised control yielded 0.75 t ha^{-1} and the fertilised treatments 1.47–1.81 t ha^{-1}; every gain exceeded the three-year $LSD_{0.05}$ of 0.046 t ha^{-1} many times over. N40P60K40 was the best treatment (1.81 t ha^{-1}, +141 % over the control), followed by N20P40K20 (1.74), N20P80K60 (1.71) and P60K40 (1.47).

The advantage of N40P60K40 over N20P40K20 was 0.07 t ha^{-1}, which is larger than the three-year $LSD_{0.05}$ and therefore significant, but modest compared with the gain obtained from the first increment of fertiliser. The treatment ranking was identical in all three years, and experimental precision was high (S_x = 1.73–1.96 % within years).

Table 5. Grain yield of repeat common bean under different mineral fertiliser rates, 2022–2024

Treatment	Grain yield, t ha^{-1}			Three-year mean, t ha^{-1}	Yield gain, t ha^{-1}	vs control, %	sig.
	2022	2023	2024				
T1 — control (no	0.73	0.76	0.77	0.75	—	—	—

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Treatment	Grain yield, t ha^{-1}			Three-year mean, t ha^{-1}	Yield gain, t ha^{-1}	vs control, %	sig.
	2022	2023	2024				
fertilizer)							
T2 — P60K40	1.51	1.48	1.41	1.47	+0.71	+95.0	*
T3 — N20P80K60	1.70	1.71	1.72	1.71	+0.96	+127.1	*
T4 — N20P40K20	1.75	1.72	1.77	1.74	+0.99	+131.5	*
T5 — N40P60K40	1.80	1.84	1.79	1.81	+1.06	+140.8	*
F value ($F_{0.05}$ = 3.84)	283.4	218.5	282.5	—	—	—	—
S_x, %	1.75	1.96	1.73	1.05	—	—	—
$LSD_{0.05}$, t ha^{-1}	0.086	0.096	0.084	0.046	—	—	—

Note: yields are means of three field replications; the three-year $LSD_{0.05}$ was computed from the error mean square pooled over years (df = 24) for n = 9 observations per treatment.

3.6. Relationship between soil nutrient status and yield

Season-mean available phosphorus was an almost perfect predictor of grain yield across the five treatments (r = 0.993; R^2 = 0.986; P = 0.001), and exchangeable potassium was nearly as good (r = 0.955; R^2 = 0.913; P = 0.011) (Fig. 3). Nitrate nitrogen was strongly but not significantly related to yield (r = 0.871; P = 0.055), and ammonium nitrogen only moderately so (r = 0.681). Among the applied rates, the nitrogen rate was significantly correlated with soil nitrate nitrogen (r = 0.919; P = 0.027) and the phosphorus rate with exchangeable potassium (r = 0.890; P = 0.043), while the remaining relationships did not reach significance at n = 5.

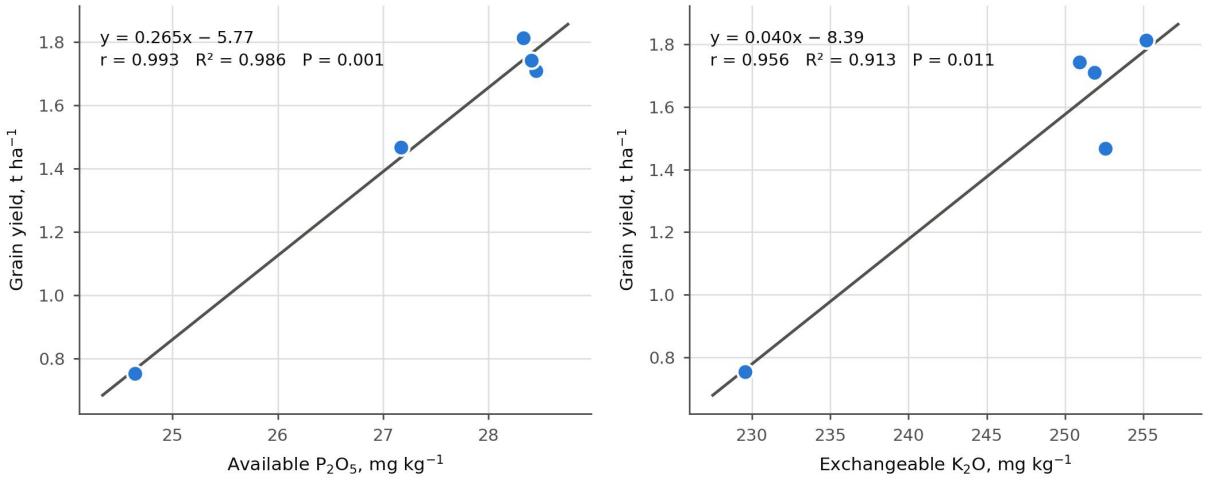


Fig. 3. Linear relationship between the season-mean content of available phosphorus (left) and exchangeable potassium (right) in the 0–30 cm layer and the three-year mean grain yield of repeat common bean. Each point is one treatment (n = 5).

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4. Discussion

The results support the hypothesis with which the experiment began. White common bean grown as a repeat crop continued to gain yield up to the highest nitrogen rate tested, 40 kg N ha^{-1}, whereas mung bean grown in the same experiment, on the same soil and in the same years reached its optimum at 20 kg N ha^{-1} and lost yield when nitrogen was doubled. The divergence is consistent with what is known about the two symbioses: common bean is a comparatively inefficient fixer whose yield depends on supplementary nitrogen unless the crop is inoculated [21, 20], while a strong fixer suffers when mineral nitrogen displaces fixation by blocking iron delivery to the nodules and depressing nitrogenase activity [22, 23, 24]. The practical inference is that fertiliser recommendations cannot be transferred between grain legumes merely because they occupy the same slot in the rotation.

The phosphorus data tell a different story from the nitrogen data. The season-mean available phosphorus pool saturated at about 28.45 mg kg^{-1}: doubling the phosphorus rate from 40 to 80 kg P_2O_5 ha^{-1} changed it by less than $LSD_{0.05}$. On a carbonate-rich sierozem this is expected, since the great majority of soil phosphorus is inorganic and strongly fixed and the labile fraction responds to land use and moisture rather than simply to the amount applied [8]. The same saturation has been reported for common bean on phosphorus-fixing Luvisols, where a moderate rate matched a high one and genotype-specific phosphorus-use efficiency mattered more than the rate itself [19], and in integrated-fertilisation trials where combining a moderate phosphorus rate with organic amendments outperformed sole mineral application [18]. Our data suggest that 60 kg P_2O_5 ha^{-1} is the practical ceiling for this crop on this soil.

The absolute optimum found here is far below the 239 kg P_2O_5 and 141 kg K_2O ha^{-1} estimated for common bean on African savanna soils [1] and below the 40 kg K_2O ha^{-1} optimum reported for Ethiopian conditions [2], which our 20–60 kg K_2O ha^{-1} range brackets. The difference is explained by the crop's position in the rotation rather than by its requirement: a repeat crop sown in mid-July follows a fertilised winter wheat, inherits its residues and grows for roughly a hundred days on a residual water allocation, so its total nutrient uptake is correspondingly smaller than that of a full-season crop.

The microbiological change was of the same order as that recorded under repeat mung bean and matches published magnitudes for legume rotations and cover crops: two- to four-fold increases in bacteria, nitrogen fixers, nitrifiers, fungi and actinomycetes [12, 13, 14]. The driver is residue quality — nitrogen-rich, easily decomposable legume residues accelerate carbon and nitrogen mineralisation and select for rapid decomposers [15] — and legume rotations specifically enrich nitrogen-cycling functional genes [16]. This is the mechanism by which a hundred-day legume improves the nutrition of the crop that follows it [9, 11, 10].

That available phosphorus explained 98.6 % of the variation in grain yield is the single most useful result for practice. It means that on this soil the phosphorus status of the ploughed layer, not the quantity of fertiliser purchased, is the proximate determinant of the yield of a repeat common bean crop — and, since the available pool saturates well below the highest rate tested, that fertiliser spent above that point buys nothing. The corollary is that soil testing for Machigin-extractable phosphorus is a more reliable basis for the fertiliser decision on these soils than a fixed rate recommendation.

The limitations are the same as for the companion study. Nodulation and the proportion of nitrogen derived from the atmosphere were not measured, so the explanation offered for the contrast between the two legumes rests on the literature rather than on direct evidence from this experiment;

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measuring nodule number, nodule mass and %Ndfa in both crops would test it directly. The microbiological determinations were made in one year without replication and are descriptive only. Phosphorus was determined as a single extractable fraction, so the fate of the applied phosphorus that did not enter the labile pool remains unresolved.

5. Conclusions

1. Mineral fertilisation of a repeat white common bean crop on irrigated stony-gravelly light sierozem soil significantly improved all measured soil nutrient indicators ($F = 9.2–585.1$ against $F_{0.05} = 3.84$), with an index of experimental precision of 0.17–1.84 %.

2. Unlike mung bean grown in the same experiment, common bean responded positively up to the highest nitrogen rate tested: N40P60K40 kg ha^{-1} gave the highest mineral nitrogen (38.98 mg kg^{-1}), exchangeable potassium (255 mg kg^{-1}) and grain yield (1.81 t ha^{-1}, +141 % over the control).

3. Available phosphorus saturated at 28.45–28.41 mg kg^{-1}, so that raising the rate from 40 to 80 kg P_2O_5 ha^{-1} produced no significant further gain; 60 kg P_2O_5 ha^{-1} is therefore the practical ceiling on this soil.

4. Growing common bean as a repeat crop increased the abundance of bacteria, free-living nitrogen fixers, nitrifiers, fungi and actinomycetes two- to more than three-fold relative to the pre-sowing state in both the 0–30 and 30–50 cm layers.

5. Season-mean available phosphorus predicted grain yield almost perfectly ($r = 0.993$; $R^2 = 0.986$), indicating that the phosphorus status of the ploughed layer, rather than the amount of fertiliser applied, governs the productivity of a repeat common bean crop on this soil.

Declarations

Author contributions. V.Yu. Isakov — conceptualisation, methodology, supervision, writing (review and editing). R. Iminchaev — investigation, field experiment, data curation, formal analysis, writing (original draft). Both authors read and approved the final manuscript.

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Conflict of interest. The authors declare no competing interests.

Data availability. The primary data of the field experiment and the complete analysis-of-variance computations are available from the corresponding author on reasonable request.

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