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Effect of long-term fertilization on nutrient uptake and harvest index under pearl millet-mustard cropping sequence in the Gird zone of Madhya Pradesh

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ABSTRACT

A long-term fertilizer experiment initiated in 2002 on a sandy clay loam Typic Ustochrepts at Gwalior, Madhya Pradesh, was used to quantify the effect of twelve nutrient-management treatments on nutrient uptake and yield of a pearl millet–mustard cropping sequence during 2024–2026. The experiment was laid out in a randomized block design with three replications. Integrated nutrient management consistently outperformed sole chemical fertilization and the unfertilized control. The treatment receiving 100% NPK + FYM @ 10 t ha⁻¹ + seed inoculation with *Azotobacter* and PSB recorded the highest N, P and K uptake in both crops: pearl millet grain and straw N uptake of 65.37 and 55.77 kg ha⁻¹ (versus 25.48 and 22.48 kg ha⁻¹ in the control), P uptake of 12.98 and 15.00 kg ha⁻¹ (versus 3.73 and 3.03 kg ha⁻¹) and K uptake of 23.69 and 115.53 kg ha⁻¹ (versus 9.77 and 34.11 kg ha⁻¹). In mustard, the same treatment produced the highest grain and straw N (83.32 and 45.47 kg ha⁻¹), P (15.33 and 16.50 kg ha⁻¹) and K (21.67 and 88.32 kg ha⁻¹) uptake against control values of 15.54 and 9.68, 2.66 and 2.95, and 4.72 and 14.49 kg ha⁻¹, respectively. Harvest index was highest under the integrated treatment in both crops (35.84% in pearl millet and 27.84% in mustard) against 30.34% and 21.40% in the control. The results demonstrate that combining organic manure and biofertilizers with the recommended fertilizer dose improves nutrient uptake and photosynthate partitioning more effectively than chemical fertilization alone, even at elevated doses and that FYM-integrated treatments sustain productivity through improved soil health rather than higher nutrient input (Paramesh *et al.*, 2023; Ranjan *et al.*, 2023).

Keywords: Integrated nutrient management, Nutrient uptake, Harvest index

Introduction

Pearl millet (*Pennisetum glaucum* L.) and Indian mustard (*Brassica juncea* L.) form one of the most important cropping sequences of the semi-arid and rainfed regions of central India, particularly in the Gird zone of Madhya Pradesh, where an *Inceptisol*-dominated, low-organic-matter soil base and erratic rainfall (600–800 mm annually) constrain sustained productivity. Continuous cultivation with imbalanced or inadequate fertilization over decades has led to widespread nutrient mining, declining native soil fertility, and yield stagnation in cereal-oilseed systems across this region (Khambalkar *et al.*, 2012) [1].

Pearl millet, though hardy and drought-tolerant, is an exhaustive feeder that removes substantial quantities of nitrogen (N), phosphorus (P) and potassium (K) from the soil, while mustard, being an oilseed crop with a high sulfur and boron requirement in addition to NPK, imposes further nutrient demand on the same land within a single agricultural year. Under such intensive double-cropping, the quantum and efficiency of nutrient uptake by both crops become critical determinants of system productivity and long-term soil sustainability. Long-term fertilizer experiments (LTFEs) conducted under the All India Coordinated Research Project on Long-Term Fertilizer Experiments have consistently demonstrated that balanced and integrated nutrient management—combining recommended NPK doses with organic manures such as farmyard manure (FYM) and biofertilizers (*Azotobacter* and phosphate-solubilizing bacteria) substantially improves nutrient uptake, yield and soil nutrient status compared to unfertilized control or fertilizer-only treatments. At Gwalior, a long-term permanent manurial trial on the pearl millet–mustard system reported that integrated application of recommended NPK, FYM (10 t ha⁻¹ yr⁻¹), and biofertilizers increased yields of pearl millet and mustard by over 100% and 130%, respectively, relative to the unfertilized control, while also improving available soil N and P (Khambalkar *et al.*, 2012) [1].

Similarly, studies on pearl millet under long-term organic and inorganic fertilization have shown that continuous FYM application, particularly across both cropping seasons, significantly enhances grain and stover nutrient concentration (N, P, K) and total nutrient uptake compared with fertilizer nitrogen alone, underscoring the complementary role of organic sources in sustaining nutrient availability over successive cropping

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cycles (Sheoran *et al.*, 2024) [2]. Likewise, recent evidence from pearl millet–mustard systems under rainfed conditions indicates that integrated moisture and nutrient management improves system productivity, nutrient uptake efficiency, and resource-use efficiency, with combined organic–inorganic–biofertilizer treatments outperforming sole inorganic fertilization (Meena *et al.*, 2025) [3].

Despite this growing body of evidence, site-specific, long-term information on the pattern of major nutrient (N, P, K) uptake and its relationship with yield performance of pearl millet and mustard under decades of continuous fertilization in the Gird agro-climatic zone remains limited. A clear understanding of how prolonged fertilizer and manure application influences nutrient partitioning between grain and stover/straw, and its consequent effect on yield, is essential for refining region-specific nutrient management recommendations and ensuring the long-term sustainability of this cropping sequence. Keeping this in view, the present investigation was undertaken to quantify the major nutrient uptake and yield of pearl millet and mustard as influenced by long-term fertilization practices in the Gird zone of Madhya Pradesh.

2. Material and Methods

The present study was conducted during 2024–2026 under an ongoing long-term fertilizer experiment initiated in 2002 at the research farm, College of Agriculture, Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya, Gwalior. The site (26°13'N, 76°10'E; 197 m above mean sea level) lies in the Gird agro-climatic zone on a uniformly levelled, well-drained field. The climate is semi-arid and sub-tropical, with summer temperatures reaching 43 °C and winter lows of 3–4 °C; the mean annual rainfall is about 730 mm, mostly received from late June to mid-September. The soil of the experimental field is alluvial sandy clay loam, classified as Typic *Ustochrepts*.

The experiment was laid out in a randomized block design with twelve treatments and three replications, giving 36 plots with a net plot size of 4.4 × 2.4 m. The twelve treatments, applied identically to both crops, were: T_1 , control; T_2 , 75% RDF-NPK; T_3 , 100% RDF-NPK; T_4 , 150% RDF-NPK; T_5 , 100% RDF-NP (without K); T_6 , 100% RDF-N (excluding P and K); T_7 , 100% NPK + 25 kg ZnSO₄ ha⁻¹; T_8 , 100% NPK + 50 kg FeSO₄ ha⁻¹; T_9 , 100% NPK + 1% foliar spray of ZnSO₄ and FeSO₄ at 25 and 45 days after sowing; T_{10} , 75% NPK + FYM @ 10 t ha⁻¹; T_{11} , 100% NPK + FYM @ 10 t ha⁻¹; and T_{12} , 100% NPK + FYM @ 10 t ha⁻¹ + seed inoculation with *Azotobacter* and PSB. Pearl millet hybrid 86M90 (*khari*) was fertilized at 80:40:20 kg N: P₂O₅: K₂O ha⁻¹ and mustard hybrid Giriraj (*rabi*) at 100:60:40 kg N: P₂O₅: K₂O ha⁻¹ according to the treatment schedule, while FYM @ 10 t ha⁻¹ was applied only in the FYM-integrated treatments (T_{10} – T_{12}).

Crops were harvested at maturity after excluding border rows and 30 cm from each plot end to eliminate border effects. Five tagged plants from each plot were harvested separately for post-harvest observations. Bundles were sun-dried for 3–4 days and weighed to record biological yield; the produce was then threshed manually, winnowed and cleaned, and grain yield was recorded, while straw/stover yield was derived by subtracting grain yield from biological yield. Harvest index (%) was computed as the ratio of grain (economic) yield to biological yield, expressed as a percentage.

Representative grain and straw samples were oven-dried at 65 ± 5 °C to constant weight, ground, and subjected to wet digestion. Nitrogen was determined by the micro-Kjeldahl method, phosphorus by the vanado-molybdate yellow colour method using a spectrophotometer, and potassium by flame photometry. Nutrient uptake (kg ha⁻¹) by grain and straw of each crop was calculated by multiplying the nutrient concentration (%) by the respective dry matter yield (kg ha⁻¹) and dividing by 100, and the total uptake was obtained by summing the grain and straw values.

The data were subjected to analysis of variance for the randomized block design, and treatment means were compared using the critical difference at 5% probability ($p \leq 0.05$).

3. Results

3.1. Total nitrogen uptake (kg ha⁻¹)

Nitrogen uptake varied significantly across nutrient management treatments in both crops. In pearl millet, grain N uptake ranged from 25.48–65.37 kg ha⁻¹ and straw from 22.48–55.77 kg ha⁻¹, with 100% NPK + FYM + *Azotobacter* + PSB seed treatment giving the highest uptake in both grain (65.37) and straw (55.77), followed by 100% NPK + FYM, 150% NPK, and 75% NPK + FYM, all significantly higher than the control (25.48/22.48 kg ha⁻¹).

In mustard, grain N uptake ranged from 15.54–83.32 kg ha⁻¹ and straw from 9.68–45.47 kg ha⁻¹. The same integrated treatment (100% NPK + FYM + *Azotobacter* + PSB) again produced the highest uptake (83.32 grain, 45.47 straw), with 150% NPK slightly outperforming 100% NPK + FYM in grain uptake, while straw uptake followed the order 100% NPK + FYM > 150% NPK > 75% NPK + FYM, all significantly exceeding the control (15.54/9.68 kg ha⁻¹).

Overall, integrated nutrient management consistently enhanced N uptake over sole chemical or control treatments.

3.2 Total phosphorus uptake (kg ha⁻¹)

Total P uptake showed significant variation across treatments in both crops. In pearl millet, grain P uptake ranged from 3.73–12.98 kg ha⁻¹ and straw from 3.03–15.00 kg ha⁻¹, with 100% NPK + FYM + *Azotobacter* + PSB seed treatment recording the highest uptake in both grain (12.98) and straw (15.00), followed by 100% NPK + FYM, 150% NPK, and 75% NPK + FYM, all significantly superior to the control (3.73/3.03 kg ha⁻¹).

In mustard, grain P uptake ranged from 2.66–15.33 kg ha⁻¹ and straw from 2.95–16.50 kg ha⁻¹. The integrated treatment (100% NPK + FYM + *Azotobacter* + PSB) again gave the highest uptake (15.33 grain, 16.50 straw), with 150% NPK marginally exceeding 100% NPK + FYM in grain P uptake, while straw uptake followed the order 100% NPK + FYM > 150% NPK > 75% NPK + FYM, all significantly higher than the control (2.66/2.95 kg ha⁻¹).

Overall, integrated nutrient management consistently maximized P uptake in both crops.

3.3. Total potassium uptake (kg ha⁻¹)

Total K uptake showed significant variation across treatments in both crops. In pearl millet, grain K uptake ranged from 9.77–23.69 kg ha⁻¹ and straw from 34.11–115.53 kg ha⁻¹, with 100% NPK + FYM + *Azotobacter* + PSB seed treatment recording the highest uptake in both grain (23.69) and straw (115.53), followed by 100% NPK + FYM, 150% NPK, and 75% NPK + FYM, all significantly superior to the control (9.77/34.11 kg ha⁻¹).

In mustard, grain K uptake ranged from 4.72–21.67 kg ha⁻¹ and straw from 14.49–88.32 kg ha⁻¹. The integrated treatment (100% NPK + FYM + *Azotobacter* + PSB) again gave the highest uptake (21.67 grain, 88.32 straw), with 150% NPK marginally exceeding 100% NPK + FYM in grain K uptake, while in straw, 150% NPK slightly surpassed 100% NPK + FYM, followed by 75% NPK + FYM, all significantly higher than the control (4.72/14.49 kg ha⁻¹).

Overall, integrated nutrient management consistently maximized K uptake in both crops.

3.5. Harvest index (HI)

Harvest index (HI) varied significantly across treatments in both crops. In pearl millet, HI ranged from 30.34–35.84%, with the highest value recorded under 100% NPK + FYM + *Azotobacter* + PSB seed treatment (35.84%), followed equally by 150% NPK and 100% NPK + FYM (35.33% each), then 100% NPK (34.28%) and 75% NPK + FYM (34.23%), all significantly higher than the control (30.34%).

In mustard, HI ranged from 21.40–27.84%, with the integrated treatment (100% NPK + FYM + *Azotobacter* + PSB) again giving the highest value (27.84%), closely followed by 150% NPK (27.71%), 75% NPK + FYM (26.92%), and 100% NPK + FYM (26.81%), all significantly exceeding the control (21.40%).

Overall, biofertilizer-integrated nutrient management consistently improved harvest index in both crops, indicating enhanced partitioning

of photosynthates toward economic yield alongside higher nutrient uptake and biomass production under integrated treatments.

Table 3.1. Impact of long-term fertilization practices on nutrient uptake and harvest index in pearl millet cropping

Treatments	N uptake (kg ha ⁻¹)		P uptake (kg ha ⁻¹)		K uptake (kg ha ⁻¹)		Harvest index
	Grain	Straw	Grain	Straw	Grain	Straw	
T ₁ : Control (no fertilizer)	25.48 ^h	22.48 ^f	3.73 ^g	3.03 ⁱ	9.77 ^g	34.11 ^h	30.34 ^e
T ₂ : 75% NPK	36.93 ^f	30.42 ^e	5.92 ^f	5.88 ^g	13.97 ^e	57.25 ^f	32.75 ^d
T ₃ : 100% NPK	46.72 ^e	36.74 ^d	7.8 ^d	8.09 ^e	17 ^d	72.16 ^e	34.28 ^{abc}
T ₄ : 150% NPK	54.85 ^c	43.71 ^c	10.11 ^b	11.26 ^c	20.48 ^b	93.49 ^c	35.33 ^{ab}
T ₅ : 100% NP	37.72 ^f	31.26 ^e	6.8 ^e	6.92 ^f	13.09 ^e	42.45 ^g	32.92 ^{cd}
T ₆ : 100% N	30.77 ^g	29.07 ^e	4.25 ^g	3.88 ^h	10.94 ^f	39.61 ^{gh}	30.48 ^e
T ₇ : 100% NPK + 25 kg/ha ZnSO ₄	48.31 ^{de}	37.57 ^d	8.07 ^d	8.97 ^d	17.56 ^{cd}	72.92 ^e	34.47 ^{ab}
T ₈ : 100 % NPK + 50 kg/ha FeSO ₄	47.75 ^e	36.99 ^d	7.75 ^d	7.67 ^e	17.31 ^d	73.45 ^e	34.65 ^{ab}
T ₉ : 100 % NPK + 1% (ZnSO ₄ + FeSO ₄) spray at 25 and 45 DAS	47.99 ^e	37.99 ^d	7.91 ^d	9.35 ^d	17.94 ^{cd}	74.02 ^e	34.57 ^{ab}
T ₁₀ : 75 % NPK + FYM	50.66 ^d	42.58 ^c	8.94 ^c	10.61 ^c	18.42 ^c	86.85 ^d	34.23 ^{bc}
T ₁₁ : 100 % NPK + FYM	58.37 ^b	49.82 ^b	10.53 ^b	11.95 ^b	21.39 ^b	105.24 ^b	35.33 ^{ab}
T ₁₂ : 100 % NPK + FYM + Seed treatment with Azotobacter + PSB	65.37 ^a	55.77 ^a	12.98 ^a	15 ^a	23.69 ^a	115.53 ^a	35.84 ^a
SEm (±)	0.62	0.55	0.12	0.17	0.24	1.22	0.340
CD (P = 0.05)	1.77	1.58	0.33	0.48	0.68	3.49	0.968

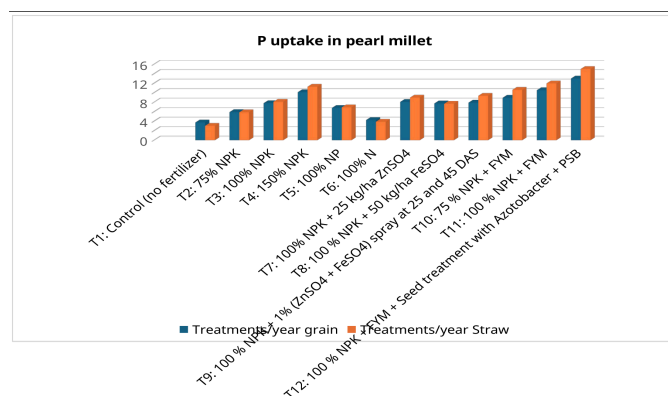
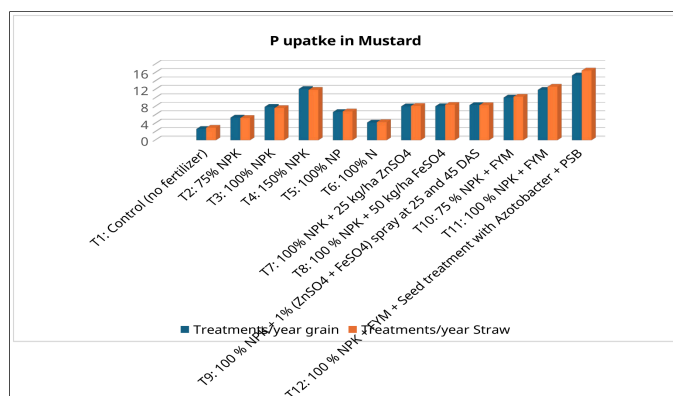
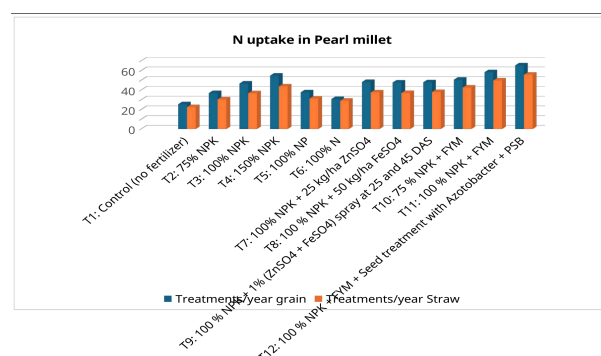
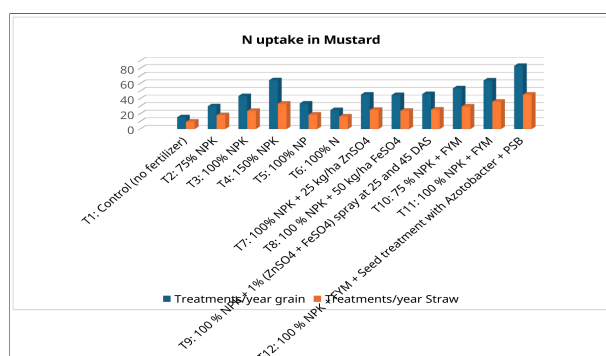
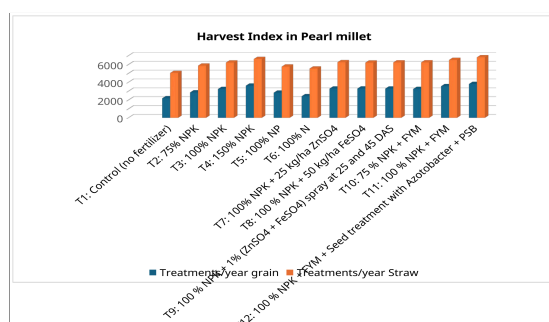
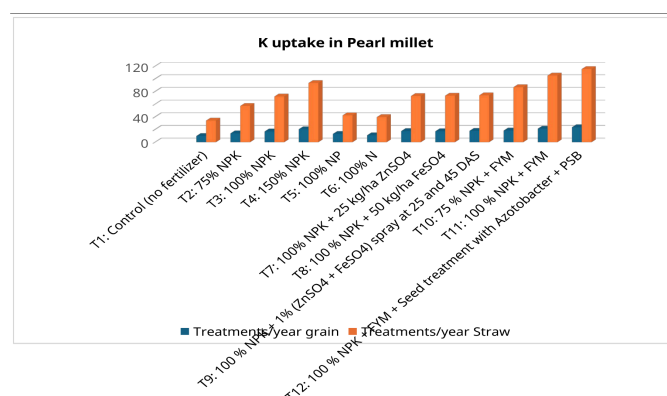
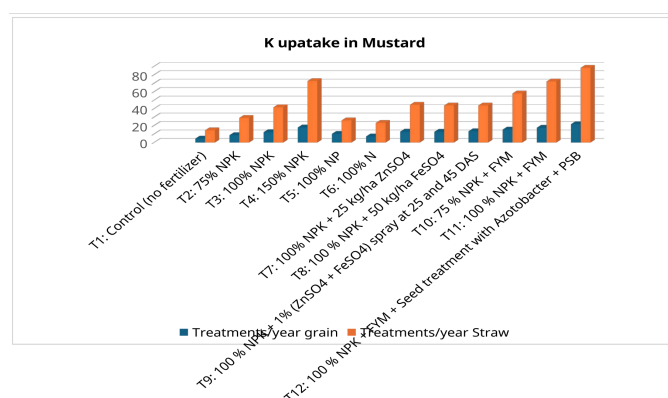
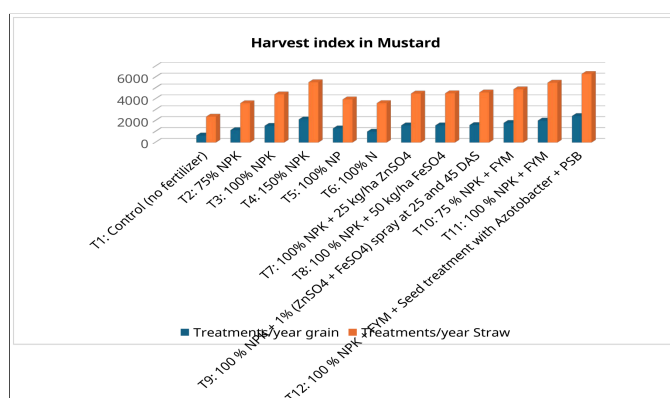


Table 3.2. Impact of long-term fertilization practices on nutrient uptake and harvest index in mustard cropping

Treatments	N uptake (kg ha ⁻¹)		P uptake (kg ha ⁻¹)		K uptake (kg ha ⁻¹)		Harvest index
	Grain	Straw	Grain	Straw	Grain	Straw	
T ₁ : Control (no fertilizer)	15.54 ^g	9.68 ^j	2.66 ^h	2.95 ^j	4.72 ^h	14.49 ⁱ	21.4 ^f
T ₂ : 75% NPK	30.06 ^e	18.32 ^h	5.35 ^f	5.26 ^h	8.71 ^f	29.07 ^f	24.07 ^e
T ₃ : 100% NPK	43.57 ^d	23.88 ^g	7.9 ^d	7.61 ^f	12.3 ^d	41.63 ^e	25.79 ^{bcd}
T ₄ : 150% NPK	64.39 ^b	33.47 ^c	12.14 ^b	11.92 ^c	17.84 ^b	72.61 ^b	27.71 ^a
T ₅ : 100% NP	33.68 ^e	18.94 ^h	6.67 ^e	6.81 ^g	10.27 ^e	26.19 ^g	24.7 ^{c e}
T ₆ : 100% N	25.03 ^f	16.52 ⁱ	4.18 ^g	4.28 ⁱ	7.19 ^g	23.19 ^h	21.64 ^f
T ₇ : 100% NPK + 25 kg/ha ZnSO ₄	45.46 ^d	25.28 ^{ef}	8.03 ^d	8.12 ^{ef}	12.92 ^d	44.59 ^d	25.93 ^b
T ₈ : 100 % NPK + 50 kg/ha FeSO ₄	44.91 ^d	24.14 ^{fg}	8.05 ^d	8.38 ^e	12.74 ^d	43.79 ^{de}	25.8 ^{bc}
T ₉ : 100 % NPK + 1% (ZnSO ₄ + FeSO ₄) spray at 25 and 45 DAS	46.18 ^d	25.63 ^e	8.32 ^d	8.29 ^e	13.33 ^d	43.76 ^{de}	25.89 ^b
T ₁₀ : 75 % NPK + FYM	53.74 ^c	29.73 ^d	10.12 ^c	10.29 ^d	15.31 ^c	57.94 ^c	26.92 ^{ab}
T ₁₁ : 100 % NPK + FYM	64.12 ^b	36.12 ^b	11.92 ^b	12.67 ^b	17.53 ^b	72.08 ^b	26.81 ^{ab}
T ₁₂ : 100 % NPK + FYM + Seed treatment with Azotobacter + PSB	83.32 ^a	45.47 ^a	15.33 ^a	16.5 ^a	21.67 ^a	88.32 ^a	27.84 ^a
SEm (±)	0.91	0.33	0.15	0.15	0.24	0.66	0.264
CD (P = 0.05)	2.58	0.94	0.44	0.43	0.69	1.89	0.753



4. Discussions

4.1 Total nitrogen uptake

Nitrogen uptake in grain and straw of both crops increased significantly with fertilization, being highest under 100% NPK + FYM + Azotobacter + PSB seed treatment (65.37 kg ha⁻¹ in grain and 55.77 kg ha⁻¹ in straw in pearl millet; 83.32 and 45.47 kg ha⁻¹ in mustard) and lowest under the unfertilized control (25.48/22.48 and 15.54/9.68 kg ha⁻¹, respectively). Nutrient uptake being a function of both nutrient concentration and dry matter production, the markedly higher N uptake under the integrated treatment resulted from the combination of higher N content and significantly higher grain and straw yields recorded in these plots (Khambalkar *et al.*, 2012) [1]. The greater N uptake under FYM-integrated treatments may be attributed

to the sustained, gradual release of nitrogen through mineralization of organic manure, which maintained a continuous supply of N throughout the crop growth period (Meena *et al.*, 2025) [3], and to biological nitrogen fixation by *Azotobacter*, which augments the soil mineral N pool and thereby enhances plant absorption (Aasfar *et al.*, 2021) [4]. Long-term organic and N fertilization studies on pearl millet have similarly demonstrated that continuous FYM application, particularly in both cropping seasons, significantly enhances grain and stover N concentration and total N uptake compared with fertilizer nitrogen alone (Sheoran *et al.*, 2024) [2]. In mustard, 150% NPK slightly outperformed 100% NPK + FYM in grain N uptake, indicating that the readily available mineral nitrogen from the higher fertilizer dose was efficiently absorbed during the reproductive phase; nevertheless, the FYM-based treatments maintained a comparable and often superior straw N uptake, reflecting slower, more synchronized N release from organic sources and reduced losses (Singh, 2020) [5].

4.2 Total phosphorus uptake

Phosphorus uptake ranged from 3.73 to 12.98 kg ha⁻¹ grain and 3.03 to 15.00 kg ha⁻¹ straw in pearl millet and from 2.66 to 15.33 and 2.95 to 16.50 kg ha⁻¹ in mustard, with the highest values under 100% NPK + FYM + *Azotobacter* + PSB (12.98/15.00 kg ha⁻¹ in pearl millet; 15.33/16.50 kg ha⁻¹ in mustard) and the lowest under control. The enhanced P uptake in the integrated and biofertilizer treatments may be ascribed to the higher availability of P in the root zone: phosphate-solubilizing bacteria release insoluble native and applied phosphates through acidification, chelation and exchange reactions (Alladi *et al.*, 2017; Jilani *et al.*, 2007) [6, 7], while organic acids released during FYM decomposition reduce P fixation on soil colloids and stimulate the microbial mineralization of organic phosphorus (Bharti *et al.*, 2017) [8]. In mustard, 150% NPK recorded marginally higher grain P uptake than 100% NPK + FYM, as expected from the larger mineral P dose applied, while the FYM-integrated treatments again dominated straw P uptake, corroborating the longer-term P-supplying capacity of organic amendments (Khambalkar *et al.*, 2012) [1]. The conspicuously low P uptake under the control (3.73 kg ha⁻¹ in pearl millet grain) reflects the continued removal of P without any external replenishment and the high P-fixing tendency of the soil, which progressively limits both soil available P and crop uptake (Rahaman *et al.*, 2024) [9].

4.3 Total potassium uptake

Potassium uptake ranged from 9.77 to 23.69 kg ha⁻¹ grain and 34.11 to 115.53 kg ha⁻¹ straw in pearl millet and from 4.72 to 21.67 and 14.49 to 88.32 kg ha⁻¹ in mustard, being highest under 100% NPK + FYM + *Azotobacter* + PSB (23.69/115.53 kg ha⁻¹ in pearl millet; 21.67/88.32 kg ha⁻¹ in mustard) and lowest under control. The predominance of K uptake in straw (e.g., 115.53 vs 23.69 kg ha⁻¹ under the integrated treatment in pearl millet) reflects the high K accumulation in vegetative tissue, particularly of pearl millet stover, consistent with the well-known luxury consumption of potassium by this crop (Singh, 2020) [5]. The higher K uptake under FYM-amended treatments may be attributed to the direct addition of K through manure, its release during mineralization of organic residues, and the improvement in soil cation exchange capacity and K retention, which sustains a larger pool of readily available potassium in soil (Pradhan *et al.*, 2024; Yadav *et al.*, 2019) [10, 11]. Imbalanced and unfertilized treatments, by contrast, showed the lowest K uptake, indicating progressive depletion of the soil K reserve under continuous cropping without adequate replenishment (Rahaman *et al.*, 2024) [9].

4.5 Harvest index

The harvest index of pearl millet ranged from 30.34 (control) to 35.84% (100% NPK + FYM + *Azotobacter* + PSB), while that of mustard ranged from 21.40 (control) to 27.84% (the integrated treatment), closely followed by 150% NPK (27.71%). The improvement in harvest index under fertilized and integrated treatments indicates better partitioning and translocation of photosynthates towards the

economic produce as a result of balanced and timely nutrient supply, which enhanced grain formation and filling. The highest harvest index under the integrated treatment, combined with the highest grain and straw yields, confirms that INM improved both total biomass production and its efficient conversion into grain, a pattern observed consistently in both a cereal and an oilseed crop (Paramesh *et al.*, 2023) [12].

5. Summary and Conclusions

The study demonstrates that integrated nutrient management consistently outperformed sole chemical fertilization or the unfertilized control across both pearl millet and mustard, for every parameter assessed: nitrogen, phosphorus, and potassium uptake, grain and straw yield, and harvest index. The treatment combining 100% NPK with FYM and *Azotobacter* + PSB seed treatment emerged as the superior option in nearly every case, recording the highest values for grain and straw N, P, and K uptake, the highest grain and straw yields, and the best harvest index in both crops. The 150% NPK and 100% NPK + FYM treatments followed closely behind, often trading second and third place depending on the nutrient and crop, while 75% NPK + FYM consistently ranked above the control but below the higher-input treatments. The control recorded the lowest values throughout, confirming the baseline nutrient-limited condition of the soil.

These results indicate that combining organic manure with biofertilizers alongside recommended chemical fertilizer doses improves nutrient availability, uptake efficiency, and photosynthate partitioning more effectively than chemical fertilization alone, even at elevated (150%) doses. The consistency of this pattern across two structurally different crops—a cereal and an oilseed—strengthens confidence that the benefit stems from improved soil biological activity and nutrient synchronization rather than crop-specific response. Long-term multi-season trials are needed to confirm the sustainability of these gains and their effect on soil health indicators. Economic analysis (cost-benefit ratio) should accompany yield data. Further studies could explore optimized *Azotobacter*–PSB strain combinations, split application timing, and performance under varying soil types and rainfall conditions.

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