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Impact of Long-Term Fertilization Practices on Soil Health under Pearl Millet–Mustard Cropping Sequence in the Gird Zone of Madhya Pradesh

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Authors' contributions

This work was carried out in collaboration among all authors. Author Shivam executed the field and laboratory experiment, performed statistical analysis, and drafted the manuscript. Author SSY conceptualized, supervised the study, and refined the manuscript protocol. Authors PAK, VKP and AC assisted in methodological validation and data interpretation. Authors KLM and BG contributed to laboratory sample processing and literature review. All authors read and approved the final manuscript.

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Abstract

Aims: To evaluate the long-term impact of integrated nutrient management practices on soil physical and chemical health parameters (bulk density, pH, EC, and available N, P, and K) in surface (0–15 cm) and sub-surface (15–30 cm) soil layers under a pearl millet–mustard cropping sequence in the Gird zone of Madhya Pradesh.

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Study Design: Randomised block design (RBD) with 12 treatments and 3 replications.
Place and Duration of Study: The study was conducted at the Research Farm, Department of Soil Science, College of Agriculture, Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya (R.V.S.K.V.V.), Gwalior (M.P.), during 2024–2026, within an ongoing long-term fertiliser experiment initiated in 2002.
Methodology: Soil samples were collected at 0–15 cm and 15–30 cm depths after pearl millet and mustard harvests across 12 fertiliser treatments, ranging from an unfertilised control to 150% NPK, micronutrient additions (Zn and Fe), and FYM combinations with biofertilisers (*Azotobacter* + PSB). Bulk density was determined using core sampling; pH and EC were measured in 1:2.5 soil-water suspensions; available N was determined using the alkaline permanganate method; available P was determined using Olsen's extractant; and available K was determined by neutral normal ammonium acetate extraction.
Results: The application of 100% NPK + FYM + seed treatment with *Azotobacter* + PSB (T12) consistently recorded superior soil health indicators. T12 achieved the lowest bulk density (1.29 Mg m^{-3} at 0–15 cm; 1.38 Mg m^{-3} at 15–30 cm) and the highest available N (278.00 and 220.83 kg ha^{-1}), P (28.97 and 22.17 kg ha^{-1}), and K (300.29 and 246.97 kg ha^{-1}) after pearl millet. Similar trends were observed following mustard harvest (N: 272.00 and 214.00 kg ha^{-1}; P: 26.65 and 19.85 kg ha^{-1}; K: 294.14 and 237.77 kg ha^{-1}). The control (T1) and sole inorganic N and NP treatments exhibited higher bulk density and pH, together with severe depletion of available nutrients.
Conclusion: Long-term integrated application of 100% NPK combined with FYM and biofertilisers significantly improves soil physical structure and chemical fertility compared with continuous inorganic or unfertilised management, offering a sustainable nutrient management strategy for the pearl millet–mustard cropping system in the Gird region.

Keywords: Long-term fertilisation; soil health; integrated nutrient management; pearl millet–mustard cropping sequence; bulk density; nutrient availability; Gird zone.

1. Introduction

The overuse of natural resources to feed a population growing at an exponential rate has presented a significant challenge to Indian agricultural systems in the post-Green Revolution era. Around the world, most agricultural soils have lost 30 to 75% of their original soil organic carbon pool, equivalent to 30–40 tonnes of carbon per hectare, much of which has been released into the atmosphere (Stavi & Lal, 2013). In addition to being crucial to the global carbon cycle, this transfer affects the soil's capacity to produce food, fibre, fuel, and building materials, raising concerns about future productivity. Soil holds nearly twice as much carbon as the atmosphere and three times as much as vegetation (Smith *et al*., 2015), and its dynamics influence atmospheric CO_2 and climate change. Declining soil organic carbon threatens soil porosity, aggregation, and water retention, whereas healthy soils sequester carbon and degraded soils become emission sources (Jackson *et al*., 2017). SOC is divided into labile and passive pools, with labile carbon serving as a sensitive indicator of management-driven changes (Li *et al*., 2018; Liu *et al*., 2013) and passive carbon forming stable humus-clay complexes. SOC also strongly influences aggregate stability (Ozlu & Kumar, 2018; Pradhan *et al*., 2024). Healthy soil underpins sustainable agriculture by supporting nutrient supply, moisture retention, and root growth. Pearl millet, a drought-tolerant C4 Kharif crop, and mustard, an economically important Rabi oilseed (Meena *et al*., 2025), together form a widely adopted, low-input sequence in water-limited rainfed ecologies.

Cropping systems significantly affect SOC (Ou *et al*., 2024), with nutrient management strategies further shaping carbon storage (Sun & Zhao, 2003), underscoring the need for site-specific soil health assessment in this cropping sequence. Morena, Bhind, Gwalior, Datia, Shivpuri, Sheopur, and portions of Tikamgarh are the seven districts that make up the Gird zone (Soni & Rai, 2024). In Madhya Pradesh's Gird agroclimatic zone, pearl millet (*Pennisetum glaucum*)–mustard (*Brassica juncea*) is a common cropping sequence that has supplanted the previous jowar–wheat system. This sequence is preferred because it provides both food and oil, has a short duration, and is adapted to limited irrigation (Parihar, 2012). Additionally, it stabilises soils in regions vulnerable to erosion and helps diversify farm revenue. Because of its high productivity and profitability, this crop sequence is popular in north-western India, particularly in Rajasthan, Uttar Pradesh, Haryana, and Madhya Pradesh; compared with other pearl millet-based systems, it requires less labour, water, and inputs (Khambalkar *et al*., 2012).

These soils are depleted in both major and minor nutrients, which reduces crop productivity. Correct and optimal application of fertilisers improves both the output and the quality of produce, and the adoption of integrated nutrient management is necessary to arrest the trend of declining output (Paramesh *et al*., 2023). Integrated nutrient management has become a crucial tool for preserving soil fertility and crop productivity and requires the optimum use of plant nutrients from organic, inorganic, and biological sources (Ranjan *et al*., 2023). When sufficient organic manures are present, the efficacy of inorganic fertilisers can be maximised, and when organic and inorganic fertilisers are used in tandem, the maximum yield of mustard and pearl millet can be achieved (Khambalkar *et al*., 2012; Singh, 2020). Long-term fertiliser experiments are crucial for assessing how chemical fertilisers and organic additives affect soil carbon accumulation through the conversion of SOC into other pools, thereby helping to measure soil quality and system sustainability (Borah *et al*., 2023).

Recent long-term field evidence from Indian cereal systems indicates that balanced mineral fertilisation integrated with organic inputs can improve soil organic carbon, nutrient availability and related soil-health attributes compared with unfertilised or solely mineral nutrient regimes (Walia *et al*., 2024). Under a pearl millet–wheat system in north-western India, long-term combined application of organic manures and mineral fertilisers was associated with improved soil organic carbon and microbiological properties relative to mineral fertilisation alone (Kumari *et al*., 2024). Other long-term experiments have likewise shown that combining organic amendments with mineral fertilisers can strengthen soil carbon pools and carbon-related soil quality indicators over extended periods (Sarkar *et al*., 2025; Das *et al*., 2025). However, evidence remains limited for the long-term response of bulk density, pH, electrical conductivity and available N, P and K across both surface and sub-surface soil layers under the pearl millet–mustard sequence in the Gird zone of Madhya Pradesh.

The present study was therefore undertaken to evaluate the long-term effects of integrated nutrient management—combining inorganic fertilisers, farmyard manure, and biofertilisers—on soil health parameters (bulk density, pH, EC, and available N, P, and K) under the pearl millet–mustard cropping sequence in the Gird zone of Madhya Pradesh, using an ongoing long-term fertiliser experiment initiated in 2002.

2. Methodology

2.1 Experimental Site and Treatments

A long-term field experiment initiated in 2002 was evaluated during 2024–2026 at the Research Farm, College of Agriculture, Rajmata Vijayaraje Scindia Krishi Vishwa Vidyalaya (R.V.S.K.V.V.), Gwalior (M.P.). The experiment was laid out in a randomised block design (RBD) with 12 treatments and 3 replications under a pearl millet–mustard cropping sequence. The treatments comprised the following: T1: Control (no fertiliser); T2: 75% NPK; T3: 100% NPK; T4: 150% NPK; T5: 100% NP; T6: 100% N; T7: 100% NPK + 25 kg ha^{-1} $ZnSO_4$; T8: 100% NPK + 50 kg ha^{-1} $FeSO_4$; T9: 100% NPK + 1% ($ZnSO_4$ + $FeSO_4$) spray at 25 & 45 DAS; T10: 75% NPK + FYM; T11: 100% NPK + FYM; T12: 100% NPK + FYM + Seed treatment with *Azotobacter* + PSB.

2.2 Soil Physico-Chemical Analysis

Soil samples were collected from surface (0–15 cm) and sub-surface (15–30 cm) depths after the harvest of pearl millet and mustard crops. Bulk density (BD, Mg m^{-3}) was determined by the standard core sampler method as BD = dry soil weight (g) / core volume (cm^3) (Pant & Ram, 2018). Soil pH was measured in a 1:2.5 soil:water suspension using a digital glass electrode pH meter (Brar *et al*., 2015; Suwara *et al*., 2016). Electrical conductivity (EC, dS m^{-1}) was recorded in the clear supernatant of the 1:2.5 soil:water suspension using a digital conductivity meter (Brar *et al*., 2015). Available nitrogen was determined by the alkaline potassium permanganate distillation method; available phosphorus was extracted using Olsen's extractant (0.5 M $NaHCO_3$, pH 8.5) and estimated spectrophotometrically; and available potassium was determined by extraction with neutral normal ammonium acetate (1N NH_4OAc, pH 7.0) followed by flame photometry (Pradhan *et al*., 2024; Sandhu *et al*., 2020). Experimental data were subjected to analysis of variance (ANOVA) for a randomised block design, and treatment means were compared using the critical difference (CD) at the 5% probability level (P = .05).

3. Results and Discussion

The effects of long-term fertilisation on soil physical and chemical parameters across two soil depths (0–15 cm and 15–30 cm) under pearl millet and mustard crops are presented in Tables 1 and 2, respectively.

3.1 Bulk Density

Bulk density at surface (0–15 cm) and sub-surface (15–30 cm) depths varied significantly among treatments after both crop harvests (Tables 1 and 2). After pearl millet, bulk density ranged from 1.29 to 1.48 Mg m^{-3} at 0–15 cm and 1.38 to 1.56 Mg m^{-3} at 15–30 cm. Treatments T12 (100% NPK + FYM + *Azotobacter* + PSB) and T11 (100% NPK + FYM) recorded the lowest bulk density (1.29 Mg m^{-3} at 0–15 cm and 1.38 Mg m^{-3} at 15–30 cm), whereas the highest bulk density was observed in control T1 (1.48 Mg m^{-3} at 0–15 cm) and 100% N T6 (1.56 Mg m^{-3} at 15–30 cm). Identical trends were observed after the mustard harvest. Several studies corroborate the present findings regarding the beneficial effects of integrated nutrient management on soil physico-chemical properties (Paramesh *et al*., 2023). Similarly, the application of organic manures such as FYM, either alone or combined with inorganic fertilisers, has been reported to decrease bulk density while improving soil porosity and water-holding capacity (Pant & Ram, 2018; Selvi *et al*., 2003; Tadesse *et al*., 2013). Bandyopadhyay *et al*. (2010) reported that the combined application of NPK and FYM increased SOC content by 29.8% compared with NPK alone under Vertisols (Kumar *et al*., 2013).

3.2 Soil pH

Soil pH showed minor but significant shifts across treatments (Tables 1 and 2). Under pearl millet, surface pH ranged from 7.52 (T4: 150% NPK) to 7.68 (T1: Control), while sub-surface pH ranged from 7.52 (T4) to 7.69 (T5: 100% NP). Integrated treatment T12 recorded lower pH values (7.56 at 0–15 cm and 7.54 at 15–30 cm) relative to the unfertilised control. The improved soil properties under FYM-integrated treatments can be attributed to continuous organic matter addition, which enhances microbial activity, promotes better soil aggregation, and improves nutrient cycling. This reduces bulk density and increases porosity and water-holding capacity (Mahmood *et al*., 2017), while simultaneously increasing organic carbon build-up and nutrient availability through slow, sustained mineralisation compared with sole chemical fertilisation (Yadav *et al*., 2019). The findings of the present investigation are in close agreement with several earlier studies that reported similar improvements in soil chemical properties under integrated and organic nutrient management practices. In alkaline soils, FYM application tends to lower pH through organic acid release during decomposition (Mahmood *et al*., 2017; Zhang *et al*., 2015), consistent with the slightly lower pH recorded under the FYM-integrated treatments in the present study.

3.3 Soil Electrical Conductivity (EC)

Electrical conductivity remained within safe, non-saline limits across all treatments (0.11 to 0.24 dS m^{-1}). Treatment T12 recorded the highest EC (0.24 dS m^{-1} at the surface and 0.18 dS m^{-1} at the sub-surface) following both crop harvests, whereas the control (T1) and 100% N (T6) recorded the lowest values (0.11 dS m^{-1}).

Table 1. Impact of long-term fertilization practices on soil health parameters after pearl millet harvest

Treatments	Bulk density ($Mg\ m^{-3}$)		Soil pH		Soil EC ($dS\ m^{-1}$)		Available N ($kg\ ha^{-1}$)		Available P ($kg\ ha^{-1}$)		Available K ($kg\ ha^{-1}$)	
	0–15 cm	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**
T1: Control (no fertilizer)	1.48a	1.54ab	7.68a	7.64b	0.11f	0.11f	149.67h	121.83g	4.25i	2.00i	163.28f	133.23g
T2: 75% NPK	1.42bc	1.49bc	7.65ab	7.68ab	0.12e	0.12e	179.67f	146.33ef	8.85g	5.55g	198.95e	155.88f
T3: 100% NPK	1.40cd	1.52abc	7.59cde	7.63bc	0.14c	0.13d	198.33e	164.00d	12.50f	8.30f	221.27d	173.09e
T4: 150% NPK	1.40cd	1.49bc	7.52f	7.52d	0.13d	0.12e	227.17d	187.33c	20.84b	15.07c	256.88c	201.46d
T5: 100% NP	1.43b	1.55a	7.65ab	7.69a	0.12e	0.12e	183.33f	151.67e	13.32de	8.85ef	172.74f	139.91g
T6: 100% N	1.47a	1.56a	7.64abc	7.66ab	0.11f	0.11f	171.00g	139.00f	5.10h	2.70h	167.88f	135.76g
T7: 100% NPK + 25 kg/ha ZnSO4	1.40cd	1.52abc	7.62bcd	7.63bc	0.13d	0.13d	207.00e	170.17d	13.67d	9.09e	226.34d	175.92e
T8: 100% NPK + 50 kg/ha FeSO4	1.37e	1.53abc	7.64abc	7.66ab	0.13d	0.13d	204.00e	167.00d	13.45de	9.00e	223.29d	174.78e
T9: 100% NPK + 1% (ZnSO4+FeSO4) spray	1.39de	1.53abc	7.64abc	7.63bc	0.14c	0.13d	200.00e	165.50d	12.95ef	8.62ef	222.32d	170.84e
T10: 75% NPK + FYM	1.32f	1.48c	7.63abcd	7.64b	0.20b	0.14c	238.17c	190.50c	17.70c	12.77d	262.14c	209.80c
T11: 100% NPK + FYM	1.29g	1.42d	7.58def	7.59c	0.20b	0.16b	261.50b	207.50b	21.15b	15.70b	287.19b	231.79b
T12: 100% NPK + FYM + Azotobacter + PSB	1.29g	1.38d	7.56ef	7.54d	0.24a	0.18a	278.00a	220.83a	28.97a	22.17a	300.29a	246.97a
SEm (±)	**0.01**	**0.01**	**0.01**	**0.01**	**0.002**	**0.002**	**2.11**	**2.12**	**0.14**	**0.13**	**2.69**	**1.99**
CD (P=.05)	**0.03**	**0.03**	**0.04**	**0.03**	**0.005**	**0.005**	**6.01**	**6.03**	**0.41**	**0.37**	**7.66**	**5.67**

Table 2. Impact of long-term fertilization practices on soil health parameters after mustard harvest

Treatments	Bulk density (Mg m⁻³)		Soil pH		Soil EC (dS m⁻¹)		Available N (kg ha⁻¹)		Available P (kg ha⁻¹)		Available K (kg ha⁻¹)	
	0–15 cm	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**	**0–15 cm**	**15–30 cm**
T1: Control (no fertilizer)	1.48a	1.54ab	7.70a	7.74a	0.11g	0.11f	145.50h	116.00h	3.60h	1.29k	153.35g	124.39g
T2: 75% NPK	1.42bc	1.49bc	7.67ab	7.71ab	0.13e	0.12e	173.50fg	140.00f	7.70g	4.25i	189.80e	148.68f
T3: 100% NPK	1.40cd	1.52abc	7.62c	7.66cd	0.14d	0.13d	193.67e	157.17e	11.35f	6.87h	213.24d	164.99e
T4: 150% NPK	1.40cd	1.49bc	7.54de	7.57f	0.12f	0.12e	220.67d	179.83c	18.75c	12.85c	246.74c	193.31d
T5: 100% NP	1.43b	1.55a	7.66abc	7.71ab	0.12f	0.11f	180.50f	145.50f	12.17e	7.52fg	163.81f	131.84g
T6: 100% N	1.47a	1.56a	7.68ab	7.69bc	0.11g	0.11f	166.00g	133.00g	4.30h	1.90j	158.01fg	127.69g
T7: 100% NPK + 25 kg/ha ZnSO4	1.40cd	1.52abc	7.67ab	7.68bcd	0.14d	0.13d	203.00e	165.00d	12.35e	7.90e	217.26d	168.94e
T8: 100% NPK + 50 kg/ha FeSO4	1.37e	1.53abc	7.65bc	7.66cd	0.13e	0.13d	201.00e	162.00de	12.25e	7.80ef	215.14d	166.88e
T9: 100% NPK + 1% (ZnSO4+FeSO4) spray	1.39de	1.53abc	7.65bc	7.64de	0.14d	0.13d	196.00e	159.50de	11.95ef	7.28g	213.11d	165.79e
T10: 75% NPK + FYM	1.32f	1.48c	7.57d	7.65cd	0.20c	0.15c	231.00c	184.50c	17.08d	11.65d	253.94c	201.76c
T11: 100% NPK + FYM	1.29g	1.42d	7.56de	7.60ef	0.21b	0.17b	254.67b	200.67b	19.87b	15.10b	269.70b	223.84b
T12: 100% NPK + FYM + Azotobacter + PSB	1.29g	1.38d	7.52e	7.59f	0.24a	0.18a	272.00a	214.00a	26.65a	19.85a	294.14a	237.77a
SEm (±)	**0.01**	**0.01**	**0.01**	**0.01**	**0.002**	**0.002**	**2.18**	**1.55**	**0.15**	**0.09**	**2.15**	**1.78**
CD (P=.05)	**0.03**	**0.03**	**0.03**	**0.03**	**0.005**	**0.004**	**6.20**	**4.41**	**0.44**	**0.25**	**6.14**	**5.08**

This response may be attributed to FYM addition supplying readily available carbon substrates that stimulate microbial proliferation and enzymatic activity, thereby accelerating organic matter decomposition and nutrient mineralisation. This continuous organic input improves soil structure, enhances cation exchange capacity, and creates a favourable microhabitat for microorganisms, thereby increasing SMBC, MBN, and DHA (Luo *et al*., 2015; Sheoran *et al*., 2020). In contrast, supra-optimal chemical fertilisation alone, without organic supplementation, may increase salt concentration and osmotic stress, suppress microbial activity, and limit the biological transformation of nutrients (Yan *et al*., 2015), despite higher applied nutrient doses. Katkar *et al*. (2011) studied the long-term effects of fertilisation and manuring on soil chemical and biological properties in Vertisols and reported that soil pH and electrical conductivity remained non-significantly affected across treatments, whereas application of 100% NPK + FYM @ 10 t ha^{-1} resulted in the highest increase in SOC and total N. The same treatment also enhanced the availability of N, P, K, and S, along with significant improvement in biological parameters such as soil microbial biomass carbon, soil microbial biomass nitrogen, and dehydrogenase activity, compared with supra-optimal fertiliser doses (150% NPK) applied without any organic amendment. These findings align closely with the results of the present investigation.

3.4 Available Nitrogen

Available nitrogen status was significantly enhanced under integrated treatments (Tables 1 and 2). After pearl millet, T12 registered the highest available N (278.00 kg ha^{-1} at 0–15 cm; 220.83 kg ha^{-1} at 15–30 cm), followed by T11 (261.50 and 207.50 kg ha^{-1}) and T10 (238.17 and 190.50 kg ha^{-1}). The control (T1) recorded the lowest available N (149.67 and 121.83 kg ha^{-1}). Similar values were maintained after the mustard harvest (T12: 272.00 and 214.00 kg ha^{-1}). The higher available nitrogen recorded under 100% NPK + FYM + *Azotobacter* + PSB and other FYM-integrated treatments may be attributed to the complementary effects of organic and biological nitrogen sources with inorganic fertilisers. FYM undergoes slow, sustained mineralisation, providing a continuous N supply, while *Azotobacter* biologically fixes atmospheric nitrogen, augmenting the soil N pool (Aasfar *et al*., 2021). Continuous organic matter addition also enhances microbial activity, accelerating N mineralisation and nitrification, besides improving soil porosity, aeration, and moisture retention, which minimises N losses through leaching and volatilisation. Additionally, PSB-mediated phosphorus availability supports better root proliferation, further enhancing nitrogen uptake and cycling compared with sole chemical fertilisation. Katkar *et al*. (2011) revealed that the combined application of NPK and FYM significantly enhanced SOC, total N, and the availability of major nutrients, along with substantial improvements in microbial biomass carbon, microbial biomass nitrogen, and dehydrogenase activity compared with supra-optimal chemical fertilisation alone, supporting the superiority of integrated nutrient management observed in the present study (Tripura *et al*., 2018). Tripura *et al*. (2018), citing Kumari *et al*. (2011), reported that continuous application of organic manure, either alone or in combination with inorganic fertiliser, significantly influenced soil microbial biomass nitrogen, with an overall increase in soil microbial biomass N after 16 years relative to the initial status (Tripura *et al*., 2018). The conjoint application of FYM with the full recommended NPK dose substantially improved organic carbon status and major nutrient availability over initial soil values, whereas imbalanced fertilisation with only NP or N alone adversely affected soil fertility, emphasising that balanced and integrated fertiliser use is essential for sustaining soil health and productivity (Verma *et al*., 2012). The combined application of crop residues, FYM, and biofertilisers enhanced carbon pools and the carbon management index, with the relative distribution and proportion of active, labile, and non-labile carbon fractions varying between surface and sub-surface soil depths depending on the cropping system (Dixit *et al*., 2020; Li *et al*., 2018), highlighting the role of diversified, integrated nutrient sources in improving carbon quality. Moharana *et al*. (2012), as cited in Naresh *et al*. (2017), reported that FYM application alone maintained the highest total organic carbon and water-soluble carbon, while the combined FYM and NPK treatment recorded the highest labile organic carbon and microbial biomass carbon, with changes in sub-surface soil carbon pools comparatively smaller than those in surface soil, underscoring the greater responsiveness of surface soil carbon fractions to organic and integrated nutrient management, consistent with trends observed in the present investigation (Naresh *et al*., 2017).

3.5 Available Phosphorus

Available phosphorus content reached its maximum under treatment T12 (28.97 kg ha^{-1} at 0–15 cm; 22.17 kg ha^{-1} at 15–30 cm after pearl millet; and 26.65 and 19.85 kg ha^{-1} after mustard). The lowest available P was recorded in the unfertilised control T1 (4.25 and 2.00 kg ha^{-1} after pearl millet; 3.60 and 1.29 kg ha^{-1} after mustard). The higher available phosphorus under 100% NPK + FYM + *Azotobacter* + PSB and other FYM-integrated treatments can be attributed to the synergistic effect of organic matter and phosphate-solubilising bacteria. PSB solubilise fixed and unavailable soil phosphorus by secreting organic acids that lower rhizosphere pH and chelate Ca, Fe, and Al ions bound to phosphate, releasing it into plant-available forms (Adnan *et al*., 2017; Jilani *et al*., 2007). FYM decomposition further releases organic acids that reduce P fixation on soil colloids while enhancing microbial activity responsible for phosphorus mineralisation (Bharti & Sharma, 2017). Additionally, improved soil porosity and organic matter content increase P diffusion and root proliferation, facilitating better uptake, whereas sole chemical fertilisation leads to greater P fixation and lower availability (Adnan *et al*., 2022; Rashid *et al*., 2019). These results collectively support the present findings, confirming that FYM combined with PSB and inorganic fertilisers enhances phosphorus solubilisation, mineralisation, and availability compared with the control and sole chemical fertilisation treatments (Alladi *et al*., 2017; Ghosh *et al*., 2021).

3.6 Available Potassium

Available potassium was highest in T12 (300.29 kg ha^{-1} at 0–15 cm; 246.97 kg ha^{-1} at 15–30 cm after pearl millet; and 294.14 and 237.77 kg ha^{-1} after mustard), significantly surpassing 100% NPK alone (T3: 221.27 and 173.09 kg ha^{-1}) and 150% NPK (T4: 256.88 and 201.46 kg ha^{-1}). The unfertilised control T1 registered the lowest values (163.28 and 133.23 kg ha^{-1}). The higher available potassium under 100% NPK + FYM + *Azotobacter* + PSB and other FYM-integrated treatments can be attributed to the continuous release of K from organic matter decomposition, which supplements the K applied through chemical fertilisers and replenishes the exchangeable K pool (Khambalkar *et al*., 2012). FYM addition also improves soil structure, porosity, and cation exchange capacity, enhancing the soil's ability to hold and retain K ions against leaching losses. Organic acids released during FYM decomposition help release fixed or non-exchangeable K from clay mineral interlayers into readily available forms (Rout *et al*., 2017). Additionally, enhanced microbial activity accelerates the mineralisation of organically bound K, while improved root proliferation under better soil physical conditions facilitates greater K uptake and turnover. In contrast, sole chemical fertilisation, lacking continuous organic input, results in lower K replenishment, greater fixation, and higher susceptibility to leaching losses, particularly in sandy clay loam soils, explaining the comparatively lower available K observed under the control and non-integrated treatments across both crops and soil depths (Rahaman *et al*., 2024). Yadav *et al*. (2019) similarly reported that FYM-treated plots maintained the highest available K (245 kg ha^{-1}), followed by FYM + NPK (214 kg ha^{-1}), NPK alone (184 kg ha^{-1}), and the control (169 kg ha^{-1}), with available K in NPK + FYM plots 18.6% higher than in NPK alone (Yadav *et al*., 2019). The present findings align with Babar and Dongale (2013), who reported significant improvement in soil available K under combined organic and inorganic fertilisation compared with sole chemical treatment. These results corroborate the present investigation, confirming that FYM combined with biofertilisers and inorganic fertilisers enhances K release, retention, and availability through improved organic matter turnover and cation exchange capacity compared with the control and sole chemical fertilisation treatments (Singh, 2020).

4. Conclusion

Long-term nutrient-management practices influenced bulk density, soil pH, electrical conductivity, and available N, P, and K at both 0–15 and 15–30 cm soil depths under the pearl millet–mustard cropping sequence. Among the evaluated treatments, 100% NPK combined with FYM and seed treatment using *Azotobacter* and phosphate-solubilising bacteria consistently recorded lower bulk density and the highest available N, P, and K after both pearl millet and mustard harvests. In contrast, the unfertilised control and treatments based solely on N or NP generally showed comparatively lower nutrient availability. The results indicate that integrating balanced mineral fertilisers with organic and biological nutrient sources can improve the selected physical and chemical indicators of soil fertility under the conditions of this long-term experiment. This integrated approach may therefore be useful for maintaining soil fertility in the studied cropping sequence. However, conclusions regarding overall system productivity, biological soil health, environmental performance, and broader sustainability require assessment of additional indicators beyond those measured in the present study.

5. Limitations

The study assessed selected soil physical and chemical indicators at two soil depths within a single long-term pearl millet–mustard experiment in the Gird zone of Madhya Pradesh. Its interpretation is therefore confined to the measured variables, treatments, soil depths, cropping sequence, and experimental conditions. Crop productivity, detailed biological indicators, greenhouse-gas emissions, and other environmental responses were not included in the present assessment. Broader evaluation of system sustainability would require these additional indicators and validation across other locations and soil conditions.

Consent

Not applicable for this soil science field study.

Ethical Approval

Not applicable for this study as no human or animal subjects were involved.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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