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Soil-plant nutrient dynamics, nutrient balance and soil biological activity of yam bean under integrated nutrient management in lateritic soil

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ABSTRACT

A field experiment was conducted during the Kharif season of 2025 at the Central Experimental Station, Wakawali, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Maharashtra, to evaluate the effects of integrated nutrient management on soil-plant nutrient dynamics, nutrient balance and soil biological activity of yam bean (*Pachyrhizus erosus* L.) grown in lateritic soil. The experiment comprised nine nutrient management treatments involving vermicompost, recommended dose of fertilizers (RDF), different phosphorus sources, Konkan Annapurna Briquettes (KAB), Azotobacter and vesicular-arbuscular mycorrhiza (VAM). Soil pH, electrical conductivity (EC), organic carbon, available N, P₂O₅ and K₂O, DTPA-extractable Fe, Mn, Zn and Cu, microbial populations, enzymatic activities, plant nutrient uptake and post-harvest N, P and K balance were evaluated. Integrated nutrient management markedly influenced soil nutrient availability, microbial population and enzymatic activities compared with the control. Treatment T₈ receiving vermicompost @ 7.5 t ha⁻¹ + RDF (P through basic slag) + Azotobacter + VAM recorded the highest soil pH (4.91), organic carbon (10.63 g kg⁻¹), available N (312.06 kg ha⁻¹), P₂O₅ (12.95 kg ha⁻¹) and K₂O (336.89 kg ha⁻¹) at harvest, compared with 4.60, 8.82 g kg⁻¹, 218.32, 10.29 and 205.68 kg ha⁻¹, respectively, in the initial soil. The highest DTPA-extractable Fe (9.90), Mn (8.93), Zn (1.09) and Cu (0.91 mg kg⁻¹) were also recorded under T₈. At 60 DAS, T₈ exhibited the highest urease (88.96 µg NH₄⁺-N g⁻¹ soil h⁻¹), dehydrogenase (77.29 µg TPF g⁻¹ soil 24 h⁻¹), acid phosphatase (55.19 µg p-NP g⁻¹ soil h⁻¹) and alkaline phosphatase (35.63 µg p-NP g⁻¹ soil h⁻¹) activities. The treatment also recorded the highest populations of bacteria (34.00 × 10⁶ cfu g⁻¹), fungi (23.00 × 10⁴ cfu g⁻¹) and actinomycetes (25.67 × 10⁵ cfu g⁻¹) at harvest. Total N, P and K uptake under T₈ reached 47.62, 12.60 and 53.09 kg ha⁻¹, respectively. Apparent nutrient balance indicated negative N, P and K balances in all fertilized treatments, while the control showed positive N and P but negative K balance. T₈ recorded apparent balances of -51.14, -92.24 and -61.85 kg ha⁻¹ for N, P and K, respectively. Overall, the integration of vermicompost, basic slag, Azotobacter and VAM improved soil nutrient availability, plant nutrient uptake and soil biological activity, while influencing post-harvest nutrient balance under lateritic soil conditions of Konkan.

Keywords: Yam bean, *Pachyrhizus erosus* L., Integrated nutrient management, Lateritic soil, Nutrient uptake, Nutrient balance, Soil microbial activity, Soil enzymes

Introduction

Yam bean (*Pachyrhizus erosus* L.) is an important tropical leguminous root crop cultivated primarily for its edible, carbohydrate-rich storage tubers and nutritional value. The crop has considerable potential for diversification of root and tuber production because of its ability to produce appreciable tuber yields under tropical conditions. As a legume, yam bean can establish symbiotic associations with nitrogen-fixing rhizobia, which contribute to its nitrogen nutrition and may reduce its dependence on externally supplied nitrogen. Its adaptation to tropical and subtropical environments further supports its potential for integration into diversified cropping systems (Sorensen *et al.*, 2023) [1].

In the Konkan region of Maharashtra, crop productivity and nutrient acquisition are influenced by the inherent characteristics of lateritic soils, which are generally acidic and often associated with low phosphorus availability. Investigations on lateritic soils of the coastal region have reported very low extractable phosphorus and a predominance of less-active and residual forms of soil phosphorus, with extractable P showing a close relationship with Al-associated phosphorus (Dongale, 1993) [2]. Similarly, studies conducted at Dapoli have characterized lateritic soils as moderately acidic, with very low available phosphorus but comparatively higher available potassium, reflecting the characteristic fertility constraints of the region (Gite *et al.*, 2019) [3]. These conditions highlight the need for nutrient-management strategies that improve nutrient availability while maintaining soil fertility.

Integrated nutrient management (INM), involving the complementary use of organic, inorganic and biological nutrient sources, offers an approach for addressing these constraints. Vermicompost supplies nutrients

gradually, contributes organic matter and provides substrates that support microbial activity and nutrient cycling, whereas inorganic fertilizers supply readily available nutrients to meet crop demand during critical growth stages. The recommended dose of fertilizers (RDF) therefore provides a basic source of major nutrients, while integration with organic and biological inputs may improve nutrient utilization and soil biological processes.

The choice of phosphorus source is particularly important in acidic lateritic soils. Single super phosphate (SSP) provides readily available phosphorus along with sulphur, whereas rock phosphate is a comparatively less-soluble source whose effectiveness is influenced by soil acidity and biological activity. Basic slag supplies phosphorus along with calcium and silicate and can also contribute to the amelioration of soil acidity. Its calcium silicate component may help neutralize acidity, while the associated phosphorus and other nutrients contribute to plant nutrition. Studies in acidic red and lateritic soils have reported improved crop productivity and nutrient availability with basic slag, particularly when combined with organic amendments such as farmyard manure (FYM) or poultry manure (Bhat *et al.*, 2010) [4]. Datta *et al.* (1972) [5] also reported beneficial effects of basic slag in acid soils through the combined supply of calcium and phosphorus. Therefore, evaluating contrasting phosphorus sources within an INM framework is relevant to improving nutrient availability in lateritic soils of Konkan.

Konkan Annapurna Briquettes (KAB), containing approximately 34:14:6 per cent N:P₂O₅:K₂O, represent another nutrient-management option for the region. Their briquetted form permits concentrated placement and simultaneous supply of major nutrients. The biological component of INM further contributes to nutrient-use efficiency. Azotobacter can contribute to biological nitrogen inputs and promote plant growth, while vesicular-arbuscular mycorrhizal (VAM) fungi enhance the effective root–soil interface and facilitate phosphorus acquisition. These functions are particularly relevant in acidic soils where phosphorus availability may be restricted through interactions with iron and aluminium oxides.

The effectiveness of INM should therefore be assessed not only through crop nutrient uptake but also through changes in soil fertility, nutrient availability and biological activity. Nutrient additions must be considered in relation to crop removal and residual soil nutrient status, since continued removal without adequate replenishment may deplete soil nutrient reserves. Integration of organic, inorganic and biological nutrient sources may improve nutrient cycling and nutrient-use efficiency while sustaining soil fertility. However, information on the combined effects of different phosphorus sources, vermicompost levels, KAB and biofertilizers on soil chemical properties, macro- and micronutrient availability, microbial populations, enzymatic activities, plant nutrient uptake and N, P and K balance in yam bean grown on lateritic soils of Konkan remains limited. Therefore, the present study was undertaken to evaluate the influence of integrated nutrient management on soil–plant nutrient dynamics, nutrient balance and soil biological activity of yam bean under lateritic soil conditions of Konkan.

Materials and Methods

A field experiment was conducted during the *Kharif* season of 2025 at the Central Experimental Station, Wakawali, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Maharashtra (17°40'–17°45' N, 73°16'–73°19' E; 167–234 m above mean sea level). The region has a hot and humid climate with an average annual rainfall of about 3000 mm. The experimental soil (Table 1) was moderately acidic (pH 4.60) with low electrical conductivity (0.10 dS m⁻¹) and these characteristics were comparable with those reported for lateritic soils of the Konkan region by Biradar (2021) [6], Mane (2020) [7] and Salvi *et al.* (2017) [8]. The soil contained 8.82 g kg⁻¹ organic carbon, 218.32 kg ha⁻¹ available nitrogen, 10.29 kg ha⁻¹ available phosphorus and 205.68 kg ha⁻¹ available potassium, indicating medium N, low P and high K status. A similar nutrient status of lateritic soils under yam bean cultivation in the Konkan region was reported by Mane (2020) [7]. The experiment was laid out in a randomized block design with nine treatments.

T₁ = Control; T₂ = VC @ 5.0 t ha⁻¹ + RDF (80:40:100 NPK kg ha⁻¹) (P through SSP); T₃ = VC @ 5.0 t ha⁻¹ + RDF (P through Rock Phosphate); T₄ = VC @ 5.0 t ha⁻¹ + RDF (P through Basic slag); T₅ = VC @ 5.0 t ha⁻¹ + RDF (N through KAB); T₆ = VC @ 7.5 t ha⁻¹ + RDF (P through SSP) + Azotobacter + VAM; T₇ = VC @ 7.5 t ha⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM; T₈ = VC @ 7.5 t ha⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM; T₉ = VC @ 7.5 t ha⁻¹ + RDF (N through KAB) + Azotobacter + VAM.

Nitrogen, phosphorus and potassium were supplied through urea, single super phosphate and muriate of potash, respectively, at 80:40:100 kg N:P₂O₅:K₂O ha⁻¹. Nitrogen was applied in two equal splits, at sowing and 45 days after sowing (DAS), while phosphorus and potassium were applied basally. Vermicompost was applied before planting at 5.0 or 7.5 t ha⁻¹ as per treatment. Rock phosphate and basic slag were broadcast and incorporated into the soil before planting. Konkan Annapurna Briquettes (34% N, 14% P₂O₅ and 6% K₂O) were point-placed at one briquette per plant at sowing and again at 45 DAS. Azotobacter and VAM were applied at 5 kg ha⁻¹ after mixing with well-decomposed manure and incorporated into the upper soil layer.

Representative surface soil samples (0–22 cm) were collected from each plot at the initial stage, 30 and 60 DAS and harvest. Soil available N, P and K were determined by the alkaline KMnO₄, Bray and Kurtz and neutral NH₄OAc extraction methods, respectively (Subbiah *et al.*, 1956; Black, 1965; Jackson, 1973) [10, 9, 11]. Soil chemical properties and enzymatic activities were assessed at 30, 60 DAS and harvest, whereas microbial populations were estimated at harvest. Populations of bacteria, fungi and actinomycetes were enumerated using the serial dilution technique (Pramer *et al.*, 1964) [12]. The experimental data were subjected to analysis of variance and treatment means were compared using the critical difference (CD) at the 0.05% level of significance as described by Panse *et al.* (1967) [13].

Table 1. Initial chemical, biological and enzymatic properties of the experimental soil

Parameter	Content	Parameter	Content
Chemical properties		Enzymatic activity	
pH (1:2.5)	4.60	Urease activity	34.34
Electrical conductivity (dS m ⁻¹)	0.10	(µg NH ₄ ⁺ –N g ⁻¹ soil hr ⁻¹)	
Organic carbon (g kg ⁻¹)	8.82	Dehydrogenase activity	27.73
Available N (kg ha ⁻¹)	218.32	(µg TPF g ⁻¹ soil 24hr ⁻¹)	
Available P ₂ O ₅ (kg ha ⁻¹)	10.29	Phosphatase activity	
Available K ₂ O (kg ha ⁻¹)	205.68	Alkaline phosphatase activity (µg <i>p</i> -NP g ⁻¹ soil hr ⁻¹)	18.34
Biological properties			

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Parameter	Content	Parameter	Content
Bacteria ($\times 10^6$ cfu g^{-1} soil)	7.00	Acid phosphatase activity	68.71
Fungi ($\times 10^4$ cfu g^{-1} soil)	10.00	(μg p -NP g^{-1} soil hr^{-1})	
Actinomycetes ($\times 10^5$ cfu g^{-1} soil)	6.00		

Soil pH

Soil pH varied significantly among treatments, ranging from 4.71–4.97, 4.70–4.87 and 4.72–4.91 at 30 DAS, 60 DAS and harvest, respectively (Table 2). Treatments integrating vermicompost with basic slag generally maintained higher soil pH, presumably due to the acid-neutralizing effect of basic slag. This finding is supported by Khan *et al.* (2007) [14], who reported an increase of about 1.0–2.0 pH units with basic slag @ 30 t ha^{-1} over the control and Nalawade *et al.* (2025) [15], who observed a similar increase in soil pH with RDF + basic slag @ 8 t ha^{-1} in lateritic soils of the Konkan region.

Soil EC

Soil EC ranged from 0.031 to 0.052, 0.030 to 0.048 and 0.027 to 0.036 $dS\ m^{-1}$ at 30 DAS, 60 DAS and harvest, respectively (Table 2). The low EC reflects the low soluble-salt status characteristic of lat-

eritic soils under high-rainfall conditions (Anonymous, 1990) [16] and is comparable with the 0.22 $dS\ m^{-1}$ reported by Pal *et al.* (2024) [17] under organic nutrient management in potato.

Soil organic carbon

Soil organic carbon ranged from 9.20 to 11.50, 9.03 to 10.77 and 8.87 to 10.63 $g\ kg^{-1}$ at 30 DAS, 60 DAS and harvest, respectively (Table 2). The higher OC under integrated nutrient management may be attributed to the addition of vermicompost and other organic inputs. Similar improvements in soil OC with organic manure application were reported by Biradar *et al.* (2021) [18] in yam bean and Diwale (2012) [19] in lateritic soils of Konkan with FYM, goat manure, vermicompost and poultry manure.

Table 2. Effect of organic, inorganic fertilizers and biofertilizer on chemical properties at various growth stages

Tr. No.	pH (1:2.5)			EC ($dS\ m^{-1}$)			Organic carbon ($g\ kg^{-1}$)		
	30	60	Harvest	30	60	Harvest	30	60	Harvest
T ₁	4.71	4.70	4.72	0.031	0.030	0.027	9.20	9.03	8.87
T ₂	4.79	4.72	4.85	0.044	0.043	0.030	10.30	10.20	9.40
T ₃	4.92	4.87	4.90	0.047	0.044	0.036	10.60	10.23	9.97
T ₄	4.97	4.80	4.91	0.052	0.040	0.032	10.67	10.30	9.90
T ₅	4.94	4.85	4.82	0.038	0.036	0.034	10.60	10.50	9.70
T ₆	4.95	4.79	4.85	0.044	0.042	0.030	11.07	10.43	10.07
T ₇	4.89	4.86	4.91	0.042	0.036	0.031	11.40	10.73	10.53
T ₈	4.92	4.83	4.91	0.049	0.048	0.030	11.50	10.77	10.63
T ₉	4.91	4.72	4.83	0.041	0.039	0.032	11.10	10.60	10.20
SE (m) $\pm$	0.05	0.04	0.03	0.003	0.003	0.002	0.35	0.22	0.27
CD ($P = 0.05$)	0.14	0.11	0.10	0.009	0.008	0.005	1.05	0.67	0.80

T₁ = Control; T₂ = VC @ 5.0 t ha^{-1} + RDF (80:40:100 NPK $kg\ ha^{-1}$) (P through SSP); T₃ = VC @ 5.0 t ha^{-1} + RDF (P through Rock Phosphate); T₄ = VC @ 5.0 t ha^{-1} + RDF (P through Basic slag); T₅ = VC @ 5.0 t ha^{-1} + RDF (N through KAB); T₆ = VC @ 7.5 t ha^{-1} + RDF (P through SSP) + Azotobacter + VAM; T₇ = VC @ 7.5 t ha^{-1} + RDF (P through Rock Phosphate) + Azotobacter + VAM; T₈ = VC @ 7.5 t ha^{-1} + RDF (P through Basic slag) + Azotobacter + VAM; T₉ = VC @ 7.5 t ha^{-1} + RDF (N through KAB) + Azotobacter + VAM.

Available nitrogen

Available nitrogen in soil was significantly influenced by integrated nutrient management, ranging from 218.47 to 300.39, 228.53 to 309.67 and 235.24 to 312.06 $kg\ ha^{-1}$ at 30 DAS, 60 DAS and harvest, respectively (Table 3). The values corresponded to low to moderate fertility status according to Bangar *et al.* (1978) [20] and were within the reported range for lateritic soils of 149–674 $kg\ ha^{-1}$ (Anonymous, 1990) [16]. The higher available N under vermicompost-based treat-

ments may be attributed to the progressive mineralization of organic N into ammonium and nitrate through microbial activity (Marschner, 2012; Saha *et al.*, 2008) [21, 22], with higher vermicompost application providing a greater substrate pool and sustained N release. Sande *et al.* (2024) [23] similarly reported that integration of vermicompost with inorganic fertilizers and bio-enriched rock phosphate improved soil properties and crop performance. An increasing trend in available N from 30 DAS to harvest was also reported by Lakshmi *et al.* (2019) [24] in potato.

Table 3. Effect of organic, inorganic fertilizers and biofertilizer on nutrient status ($kg\ ha^{-1}$) at various growth stages

Tr. No.	Available N			Available P_2O_5			Available K_2O		
	30	60	Harvest	30	60	Harvest	30	60	Harvest
T ₁	218.47	228.53	235.24	12.92	10.02	8.4	203.25	220.68	210.96
T ₂	269.10	273.68	263.91	17.35	11.41	10.76	258.43	264.79	255.08
T ₃	277.61	279.10	285.77	18.62	12.8	11.47	303.60	317.00	304.84
T ₄	278.45	279.36	286.42	18.64	12.94	11.74	317.24	324.59	313.69
T ₅	275.83	274.86	277.25	18.3	12.45	11.2	297.19	300.41	296.51
T ₆	292.55	282.63	299.89	19.08	13.63	11.95	322.00	332.15	314.18

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Tr. No.	Available N			Available P ₂ O ₅			Available K ₂ O		
	30	60	Harvest	30	60	Harvest	30	60	Harvest
T ₇	298.97	291.65	310.88	19.79	14.23	12.73	335.00	339.15	331.16
T ₈	300.39	309.67	312.06	19.82	14.45	12.95	342.46	349.82	336.89
T ₉	293.76	287.49	304.08	19.26	13.97	12.34	326.75	334.20	315.28
SE (m) ±	7.73	7.16	12.78	0.86	0.89	0.60	11.46	13.61	16.11
CD (P = 0.05)	23.17	21.45	38.30	2.57	2.66	1.80	34.35	40.81	48.30

T₁ = Control; T₂ = VC @ 5.0 t ha⁻¹ + RDF (80:40:100 NPK kg ha⁻¹) (P through SSP); T₃ = VC @ 5.0 t ha⁻¹ + RDF (P through Rock Phosphate); T₄ = VC @ 5.0 t ha⁻¹ + RDF (P through Basic slag); T₅ = VC @ 5.0 t ha⁻¹ + RDF (N through KAB); T₆ = VC @ 7.5 t ha⁻¹ + RDF (P through SSP) + Azotobacter + VAM; T₇ = VC @ 7.5 t ha⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM; T₈ = VC @ 7.5 t ha⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM; T₉ = VC @ 7.5 t ha⁻¹ + RDF (N through KAB) + Azotobacter + VAM.

Available phosphorous

Available P₂O₅ in soil ranged from 12.92 to 19.82, 10.02 to 14.45 and 8.40 to 12.95 kg ha⁻¹ at 30 DAS, 60 DAS and harvest, respectively (Table 3). These values were within the reported range of 0.35–74.14 kg ha⁻¹ for lateritic soils, with a mean of 14.14 kg ha⁻¹ (Anonymous, 1990) [16]. The relatively higher P availability under integrated nutrient management may be attributed to the synergistic effect of N with P and the continuous release of available P through organic matter mineralization (Shrivastava, 2002; Tisdale et al., 1995) [25, 26]. Organic amendments may further reduce P fixation by coating Fe and Al sesquioxides, thereby increasing P availability in lateritic soils (Tandon, 1987) [27]. The subsequent decline in available P from 30 DAS to harvest may be associated with crop uptake and fixation, similar to the decrease reported by Moharana et al. (2014) [28] in green gram. Mamatha et al. (2018) [29] also reported increased soil pH and available P₂O₅ with 100% RDF + basic slag @ 2 t ha⁻¹ in paddy.

Available potassium

Available K₂O in soil ranged from 203.25 to 342.46, 220.68 to 349.82 and 210.96 to 336.89 kg ha⁻¹ at 30 DAS, 60 DAS and harvest, respectively (Table 3), corresponding to moderate to high fertility status according to Bangar et al. (1978) [20]. These values were within the reported range of 11–1152 kg ha⁻¹ for lateritic soils, with an average of 226 kg ha⁻¹ (Anonymous, 1990) [16]. The higher available K under T₈ consisting vermicompost @ 7.5 t ha⁻¹ + basic slag + Azotobacter + VAM may be attributed to enhanced nutrient cycling and K release from vermicompost, together with improved nutrient availability under integrated nutrient management. The accompanying basic slag may also have modified the acidic soil environment through its Ca²⁺ and silicate-containing constituents, thereby favouring nutrient availability. A similar increase in soil K with integrated organic and inorganic nutrient management was reported by Harmalkar (2018) [30], who recorded the highest K under 100% RDF + FYM @ 10 t ha⁻¹ at

different growth stages of sweet potato, followed by a decline towards harvest due to crop uptake.

DTPA extractable micronutrients

DTPA-extractable micronutrients (Fe, Mn, Zn and Cu) were influenced by integrated nutrient management, with T₈ receiving VC @ 7.5 t ha⁻¹ + RDF with P through basic slag + Azotobacter + VAM generally recording the highest availability throughout the crop period (Table 4). DTPA-extractable Fe ranged from 5.83–10.10 mg kg⁻¹, with T₈ recording 10.10, 9.97 and 9.90 mg kg⁻¹ at 30 DAS, 60 DAS and harvest, respectively and remaining statistically at par with T₇ and T₉ at most stages. Similarly, available Mn ranged from 3.77–8.87 mg kg⁻¹, while T₈ recorded 8.87, 8.77 and 8.93 mg kg⁻¹ at the respective stages. The availability of Zn varied from 0.48–1.23, 0.51–1.25 and 0.45–1.09 mg kg⁻¹, whereas Cu ranged from 0.43–1.06, 0.41–0.96 and 0.38–0.91 mg kg⁻¹ at 30 DAS, 60 DAS and harvest, respectively. The maximum values for both Zn and Cu were consistently recorded under T₈.

The enhanced micronutrient availability under integrated nutrient management may be associated with the addition of vermicompost and biological inputs, which can increase organic matter-derived complexation, microbial activity and nutrient cycling, thereby influencing the availability of micronutrients in soil. Dhane et al. (1995) [31] reported positive relationships of DTPA-extractable Zn and Mn with soil organic carbon, clay and cation exchange capacity, while Fe and Cu were also positively associated with organic carbon. Regional studies under Konkan conditions have documented considerable variation in available micronutrients in Wakawali soils (Diwan, 1982; Pereira, 1983) [32, 33]. Bhattacharyya et al. (2018) [34] reported DTPA-extractable Fe, Mn and Cu contents of 11.83, 40.74 and 0.33 mg kg⁻¹, respectively, in bench-terraced soils of Wakawali. The present results therefore indicate that integrated application of organic, inorganic and biological nutrient sources can favour the availability of micronutrients in lateritic soils.

Table 4. Effect of organic, inorganic fertilizers and biofertilizer on DTPA extractable micronutrients (mg kg⁻¹) at various growth stages

Tr. No.	Fe			Mn			Zn			Cu		
	30	60	Harvest	30	60	Harvest	30	60	Harvest	30	60	Harvest
T ₁	5.83	5.23	5.13	3.77	3.57	4.77	0.48	0.51	0.45	0.43	0.41	0.38
T ₂	6.67	5.67	5.53	5.17	4.6	5.67	0.57	0.60	0.54	0.50	0.45	0.43
T ₃	8.17	6.97	6.50	6.1	5.77	6.73	0.78	0.80	0.70	0.67	0.62	0.55
T ₄	8.20	7.47	7.20	6.13	6.13	6.8	0.79	0.82	0.72	0.69	0.67	0.62
T ₅	7.20	6.47	6.17	5.37	4.77	6.13	0.67	0.70	0.64	0.56	0.54	0.51
T ₆	8.33	8.00	7.97	7.00	6.47	7.33	0.94	0.99	0.78	0.73	0.70	0.64
T ₇	9.77	9.57	8.93	8.27	8.1	8.13	1.17	1.09	1.08	0.92	0.86	0.79
T ₈	10.10	9.97	9.90	8.87	8.77	8.93	1.23	1.25	1.09	1.06	0.96	0.91
T ₉	9.47	9.30	9.00	7.40	7.27	7.87	1.01	1.04	1.02	0.77	0.74	0.74
SE (m) ±	0.55	0.53	0.34	0.28	0.28	0.26	0.08	0.06	0.04	0.03	0.05	0.03
CD (P = 0.05)	1.64	1.59	1.03	0.84	0.83	0.79	0.24	0.18	0.13	0.08	0.14	0.09

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T₁ = Control; T₂ = VC @ 5.0 t ha⁻¹ + RDF (80:40:100 NPK kg ha⁻¹) (P through SSP); T₃ = VC @ 5.0 t ha⁻¹ + RDF (P through Rock Phosphate); T₄ = VC @ 5.0 t ha⁻¹ + RDF (P through Basic slag); T₅ = VC @ 5.0 t ha⁻¹ + RDF (N through KAB); T₆ = VC @ 7.5 t ha⁻¹ + RDF (P through SSP) + Azotobacter + VAM; T₇ = VC @ 7.5 t ha⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM; T₈ = VC @ 7.5 t ha⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM; T₉ = VC @ 7.5 t ha⁻¹ + RDF (N through KAB) + Azotobacter + VAM.

Microbial population

The population of fungi, bacteria and actinomycetes was markedly influenced by integrated nutrient management, with T₈ receiving vermicompost @ 7.5 t ha⁻¹ + RDF (P through basic slag) + Azotobacter + VAM recording the highest populations of 34.00×10^4 , 25.67×10^6 and 23.00×10^5 cfu g⁻¹ soil, respectively (Table 5), compared with the lowest populations of 12.33×10^4 , 8.33×10^6 and 7.33×10^5 cfu g⁻¹ soil under the control (T₁). Among the remaining treatments, T₉, T₇ and T₆ also maintained comparatively higher fungal and bacterial populations, while T₇ and T₉ recorded higher actinomycetes populations.

The enhanced microbial populations under integrated treatments may be attributed to the synergistic effect of vermicompost, inorganic fertilizers and biofertilizers. Vermicompost provides organic carbon, nutrients and readily decomposable substrates that support microbial multiplication and the decomposition of organic residues, while Azotobacter and VAM may further enhance rhizospheric biological activity and nutrient cycling. The comparatively lower microbial populations under the control may be associated with limited availability of organic substrates and nutrients. These findings are supported by Shukla *et al.* (1998) [35], who demonstrated that fertilizer management influenced soil microbial populations and enzyme activities in potato field soils.

Urease enzymatic activity

Soil urease activity varied among treatments and growth stages, ranging from 36.87–56.86, 52.24–88.96 and 41.45–58.89 µg NH₄⁺-N g⁻¹ soil h⁻¹ at 30 DAS, 60 DAS and harvest, respectively (Table 5). The highest activity was recorded under treatment T₈ receiving VC @ 7.5 t ha⁻¹ + RDF (P through basic slag) + Azotobacter + VAM, which may be attributed to the synergistic effects of vermicompost and microbial inoculants that enhanced microbial proliferation, organic substrate availability and N transformations. Similar enhancement of soil enzyme activity under integrated nutrient management in yam bean grown on lateritic soils of Konkan was reported by Mane (2020) [7]. Comparable responses were also observed by Sahoo *et al.* (2014) [36] in elephant foot yam with FYM @ 10 t ha⁻¹ + NPK @ 100:60:100 kg ha⁻¹ and by Rai *et al.* (2011) [37] following organic nutrient application.

Dehydrogenase enzymatic activity

Dehydrogenase activity was significantly influenced by vermicompost, inorganic fertilizers and biofertilizers across the growth stages of yam bean, ranging from 31.08–65.86, 38.83–88.96 and 23.94–38.82 µg TPF g⁻¹ soil 24 h⁻¹ at 30 DAS, 60 DAS and harvest, respectively (Table 5). The activity increased up to 60 DAS, probably due to vigorous root growth and greater rhizodeposition, which supplied substrates for microbial metabolism, followed by a decline at harvest owing to reduced root activity and depletion of readily available carbon substrates. The highest activity under T₈ receiving VC @ 7.5 t ha⁻¹ + RDF (P through basic slag) + Azotobacter + VAM indicates the synergistic contribution of organic amendment and microbial inoculants to soil biological activity. Similar dehydrogenase activity in yam bean grown on lateritic soils of Konkan was reported by Mane (2020) [7], while Salvi *et al.* (2021) [38] observed enhanced microbial population and CO₂ evolution with increasing inorganic fertilizer and FYM application at CES, Wakawali, DBSKKV, Dapoli. Rai *et al.* (2011) [37] and Simon (2014) [39] also reported increased dehydrogenase activity with integrated nutrient management and FYM application, respectively.

Acid phosphatase enzymatic activity

Acid phosphatase activity was significantly influenced by vermicompost, inorganic fertilizers and biofertilizers across the growth stages of yam bean, ranging from 50.60–67.09, 51.95–69.52 and 50.81–66.87 µg p-NP g⁻¹ soil h⁻¹ at 30 DAS, 60 DAS and harvest, respectively (Table 5). A slight increase in activity up to 60 DAS followed by a decline at harvest was observed in most treatments, which may be associated with active root growth and microbial activity during crop development and reduced biological activity towards maturity. The response under different P sources may also be related to the low solubility of rock phosphate and basic slag compared with highly soluble SSP, while Fe and Al interactions in lateritic soils can influence P availability and promote phosphatase-mediated P mineralization. Laxminarayana (2017) [40] reported the highest acid phosphatase activity (82.20 µg p-NP g⁻¹ soil h⁻¹) with VAM + lime + FYM + NPK in yam bean and observed its significant association with tuber yield and biochemical characteristics. Similarly, Madhavi *et al.* (2014) [41] reported greater acid phosphatase activity under integrated organic and inorganic nutrient management, with activity increasing during active crop growth and declining towards maturity.

Alkaline phosphatase enzymatic activity

Alkaline phosphatase activity varied among treatments and growth stages of yam bean, ranging from 18.55–34.38, 18.90–35.63 and 18.58–35.47 µg p-NP g⁻¹ soil h⁻¹ at 30 DAS, 60 DAS and harvest, respectively (Table 5). The lowest activity was recorded in the absolute control (T₁), whereas T₈ consisting VC @ 7.5 t ha⁻¹ + RDF (P through basic slag) + Azotobacter + VAM consistently recorded the highest activity at all stages, followed by T₇ and T₉ at harvest (35.12 and 33.61 µg p-NP g⁻¹ soil h⁻¹, respectively). The enhanced activity under integrated nutrient management may be attributed to the combined supply of organic substrates, mineral nutrients and beneficial microorganisms, which stimulated microbial proliferation and extracellular phosphatase production involved in organic P mineralization. Basic slag-containing treatments also showed higher activity than their corresponding SSP treatments; at harvest, T₄ and T₈ recorded 25.69 and 35.47 µg p-NP g⁻¹ soil h⁻¹ compared with 21.35 and 27.23 µg p-NP g⁻¹ soil h⁻¹ in T₂ and T₆, respectively, suggesting greater P-transforming microbial activity under these integrated combinations. Laxminarayana (2017) [40] similarly reported acid and alkaline phosphatase activities of 82.20 and 67.02 µg p-NP g⁻¹ soil h⁻¹, respectively, under VAM + NPK + FYM in yam bean grown on acid Alfisol.

Nutrient uptake of yam bean

Total N, P and K uptake varied considerably among the treatments, with T₈ receiving VC @ 7.5 t ha⁻¹ + RDF (P through basic slag) + Azotobacter + VAM recording the highest uptake of 47.62, 12.60 and 53.09 kg ha⁻¹, respectively (Table 6), compared with 10.76, 3.44 and 12.77 kg ha⁻¹ in the absolute control (T₁). Among treatments receiving VC @ 5.0 t ha⁻¹, T₄ recorded the highest N, P and K uptake (27.34, 6.72 and 30.46 kg ha⁻¹, respectively), whereas T₈ was superior among the corresponding 7.5 t ha⁻¹ vermicompost treatments, followed by T₇ and T₉ for K uptake (47.75 and 42.86 kg ha⁻¹, respectively). Increasing vermicompost from 5.0 to 7.5 t ha⁻¹ along with biofertilizer inoculation increased the mean N, P and K uptake by 91.4, 78.1 and 85.8%, respectively, indicating improved nutrient acquisition under integrated nutrient management. The marked improvement from T₄ to T₈, with N, P and K uptake increasing from 27.34 to 47.62, 6.72 to 12.60 and 30.46 to 53.09 kg ha⁻¹, respectively, demonstrates the combined contribution of higher vermicompost addition and Azotobacter + VAM to nutrient uptake.

These findings are supported by Stamford *et al.* (2007) [42], who reported enhanced P uptake in *Pachyrhizus erosus* under phosphate-rock-based biofertilization in acidic soil. Rajput *et al.* (2011) [43] and Mohanty *et al.* (2014) [44] similarly observed improved N, P and K uptake with integrated vermicompost/inorganic nutrient management in french bean and potato, respectively. Mamatha *et al.* (2018) [29] conducted a field experiment on paddy in acidic soil of Karnataka.

Basic slag was applied along with RDF. The treatment 100% RDF + basic slag @ 2 t ha⁻¹ recorded the highest grain yield (50.32 q ha⁻¹) and straw yield (65.93 q ha⁻¹). Similar findings were reported by Castellanos (1997) [45] in Mexican yam bean, where phosphorus uptake was reported to be approximately 39-41 kg ha⁻¹, while potassium uptake ranged from 241-266 kg ha⁻¹.

Table 5. Effect of organic, inorganic fertilizers and biofertilizer on microbial populations and enzymatic activity of soil at different growth stages

Tr. No.	Microbial population (At harvest)			Enzymatic activities											
	Fungi x10 ⁻⁴	Actinomycetes x10 ⁻⁵	Bacteria x10 ⁻⁶	Urease (µg NH ₄ -N g ⁻¹ soil hr ⁻¹)			Dehydrogenase (µg TPF g ⁻¹ soil 24 hr ⁻¹)			Phosphatase (µg p-NP g ⁻¹ soil hr ⁻¹)					
										Acid			Alkaline		
				30	60	Harvest	30	60	Harvest	30	60	Harvest	30	60	Harvest
T ₁	12.33	7.33	8.33	36.87	52.24	41.45	31.08	38.83	23.94	67.09	69.52	66.28	18.55	18.9	18.58
T ₂	16.33	8.67	12.33	47.54	54.18	50.47	38.12	41.23	27.80	61.47	64.2	62.75	20.95	21.77	21.35
T ₃	25.00	15.00	14.00	49.84	58.94	52.59	41.59	49.16	29.93	61.79	66.8	65.4	23.29	25.08	24.07
T ₄	28.00	18.00	14.67	50.30	59.81	54.73	46.72	53.57	30.72	59.67	66.12	65.14	24.32	26.2	25.69
T ₅	23.00	13.00	15.33	48.55	57.19	51.23	41.51	49.00	28.51	62.58	68.99	66.87	23.15	25.05	24.05
T ₆	31.67	20.67	18.67	52.07	60.27	54.83	48.84	54.20	33.95	50.6	51.95	50.81	29.2	33.62	27.23
T ₇	32.33	21.33	20.67	56.68	77.58	57.97	58.22	68.86	36.55	55.47	56.05	55.38	33.76	35.49	35.12
T ₈	34.00	23.00	25.67	56.86	88.96	58.89	65.86	77.29	38.82	53.93	55.19	54.58	34.38	35.63	35.47
T ₉	33.33	21.67	19.00	52.83	66.94	54.92	51.44	57.20	36.08	56.57	57.69	57.47	31.18	33.97	33.61
SE (m)	1.289	0.922	0.766	1.02	1.28	1.72	5.12	7.14	1.78	2.27	2.08	1.22	0.98	0.85	0.76
±															
CD (P = 0.05)	3.865	2.765	2.296	3.06	3.84	5.16	15.35	21.40	5.35	6.8	6.23	3.66	2.94	2.55	2.27

Table 6. Nutrient uptake by plants and tuber of yam bean under various treatments

Tr. No.	Treatment details	Nutrient uptake (kg ha ⁻¹)								
		Nitrogen			Phosphorous			Potassium		
		Plants	tuber	total	Plants	tuber	total	Plants	tuber	total
T ₁	Control	8.35	2.41	10.76	2.57	0.87	3.44	10.73	2.03	12.77
T ₂	VC @ 5.0 t ha ⁻¹ + RDF (80:40:100 NPK kg ha ⁻¹) (P through SSP)	10.23	6.45	16.68	3.55	1.36	4.91	13.94	3.95	17.89
T ₃	VC @ 5.0 t ha ⁻¹ + RDF (P through Rock Phosphate)	13.99	9.41	23.40	4.23	2.03	6.26	19.56	7.10	26.66
T ₄	VC @ 5.0 t ha ⁻¹ + RDF (P through Basic slag)	16.60	10.74	27.34	4.48	2.24	6.72	21.27	9.18	30.46
T ₅	VC @ 5.0 t ha ⁻¹ + RDF (N through KAB)	11.17	8.51	19.68	3.71	1.81	5.52	15.32	6.00	21.33
T ₆	VC @ 7.5 t ha ⁻¹ + RDF (P through SSP) + Azotobacter + VAM	19.11	14.31	33.43	5.55	2.61	8.17	24.55	10.73	35.29
T ₇	VC @ 7.5 t ha ⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM	26.24	17.03	43.26	7.49	3.50	10.99	35.43	12.32	47.75
T ₈	VC @ 7.5 t ha ⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM	28.37	19.24	47.62	8.68	3.92	12.60	38.76	14.32	53.09
T ₉	VC @ 7.5 t ha ⁻¹ + RDF (N through KAB) + Azotobacter + VAM	26.49	15.88	42.38	7.13	2.79	9.93	31.26	11.59	42.86
	SE (m) ±	2.38	0.85	2.42	0.85	0.190	0.93	3.84	0.97	3.76
	CD (P = 0.05)	7.12	2.54	7.25	2.54	0.569	2.79	11.53	2.92	11.26

Balance sheet of nitrogen

The balance sheet of available nitrogen (N) in soil after harvest of yam bean as influenced by different nutrient management treatments is presented in Table 7. The initial available N content of the soil was 218.32 kg ha⁻¹. In the absolute control (T₁), after accounting for crop uptake of 10.76 kg ha⁻¹, the expected available N was 207.56 kg ha⁻¹, whereas the actual post-harvest value was 235.24 kg ha⁻¹, resulting in an apparent net gain of 27.68 kg ha⁻¹. This gain may be attributed to mineralization of native soil organic matter, decomposition

of residual organic materials and biological N transformations during the crop period. In the fertilized treatments, the final available N before accounting for crop uptake ranged from 371.32 to 410.82 kg ha⁻¹. However, the apparent losses varied considerably among treatments, reflecting differences in N recovery and transformation.

The apparent N losses may be associated with the dynamic behaviour of inorganic N in soil. Nitrogen from urea is rapidly hydrolysed to ammoniacal N and subsequently nitrified to nitrate, which is susceptible to leaching under the high-rainfall conditions and well-drained lateritic soils of Konkan. Additional losses may occur through ammonia

volatilization and denitrification depending on soil moisture, temperature, fertilizer placement and other environmental conditions. T₂ receiving VC @ 5 t ha⁻¹ + RDF through SSP, despite receiving 155 kg N ha⁻¹, recorded the highest apparent N loss (92.73 kg ha⁻¹), coinciding with relatively low crop uptake (16.68 kg ha⁻¹). In contrast, T₈ receiving VC @ 7.5 t ha⁻¹ + RDF (P through basic slag) + Azotobacter + VAM recorded the highest N uptake (47.62 kg ha⁻¹) and the lowest apparent N loss among the fertilized treatments (51.14 kg ha⁻¹). The comparatively efficient N recovery under T₈ may be attributed to the gradual N release from vermicompost, improved microbial activity and nutrient retention, together with the complementary effects of Azotobacter and VAM on biological N supply, root development and nutrient acquisition.

Balance sheet of phosphorous

The balance sheet of available P₂O₅ after harvest showed marked differences among nutrient management treatments (Table 8). The initial available P₂O₅ content was 10.29 kg ha⁻¹. In the absolute control (T₁), the expected balance after crop uptake (3.44 kg ha⁻¹) was 6.85 kg ha⁻¹, whereas the actual post-harvest value was 8.40 kg ha⁻¹, resulting in an apparent net gain of 1.55 kg ha⁻¹. In contrast, the fertilized treatments showed substantial apparent P losses (70.57–97.67 kg ha⁻¹), with the highest loss in T₆ receiving VC @ 7.5 t ha⁻¹ + RDF-P through SSP and the lowest in T₅ receiving VC @ 5 t ha⁻¹ + RDF-N-UB. The large difference between expected and actual available P₂O₅ may be attributed to the strong P fixation and transformation in acidic lateritic soils, where Fe and Al oxides readily adsorb or precipitate phosphate into less available forms.

Phosphorus recovery also varied with the source of P. The relatively soluble P supplied through SSP is rapidly available but is more prone to fixation in acidic soils, whereas rock phosphate undergoes slower dissolution, which can be enhanced under acidic conditions by organic acids and microbial activity. Basic slag supplies P along with Ca and silicate-bearing compounds, which may modify the soil chemical environment and influence P availability. Despite the considerable apparent P losses, integrated nutrient management, particularly with higher vermicompost and biofertilizer application, improved crop P acquisition. The highest P₂O₅ uptake was recorded in T₈ consisting VC @ 7.5 t ha⁻¹ + RDF-P through basic slag + Azotobacter + VAM (12.60 kg ha⁻¹), followed by T₇ (10.99 kg ha⁻¹) and T₉ (9.93 kg ha⁻¹). Enhanced P uptake under these treatments may be as-

sociated with improved root development, microbial activity and P mobilization, with VAM increasing the soil volume explored by roots and facilitating P acquisition beyond the immediate rhizosphere.

Balance sheet of potassium

The balance sheet of available K after harvest of yam bean showed considerable variation among nutrient management treatments (Table 9). The initial available K content was 205.68 kg ha⁻¹. In the absolute control (T₁), crop uptake of 12.77 kg ha⁻¹ resulted in an expected balance of 192.91 kg ha⁻¹, whereas the actual post-harvest available K was 175.80 kg ha⁻¹, indicating an apparent net loss of 17.11 kg ha⁻¹. In the fertilized treatments, K addition ranged from 74 to 190 kg ha⁻¹, with crop uptake ranging from 17.89 to 53.09 kg ha⁻¹ and apparent K losses from 4.09 to 135.22 kg ha⁻¹. The highest apparent loss was recorded in T₂ receiving VC @ 5 t ha⁻¹ + RDF-P through SSP; 135.22 kg ha⁻¹, whereas the lowest was observed in T₉ receiving VC @ 7.5 t ha⁻¹ + RDF-N-UB + Azotobacter + VAM; 4.09 kg ha⁻¹.

The highest K uptake was recorded in T₈ receiving VC @ 7.5 t ha⁻¹ + RDF-P through basic slag + Azotobacter + VAM (53.09 kg ha⁻¹), followed by T₇ (47.75 kg ha⁻¹) and T₉ (42.86 kg ha⁻¹). Despite its high K uptake, T₈ retained 280.74 kg ha⁻¹ available K after harvest and showed an apparent loss of 61.85 kg ha⁻¹, suggesting greater recovery of applied K in the soil-plant system under integrated nutrient management. The relatively high apparent loss in T₂ may be associated with its high K addition (160 kg ha⁻¹) relative to crop uptake (17.89 kg ha⁻¹), together with redistribution of K among soil pools and possible losses from the soil system. Potassium supplied through fertilizer rapidly enters the soil solution and may subsequently be absorbed by plants or retained on soil exchange sites, while its balance is also influenced by crop removal and soil K transformations.

Negative K balances have also been reported in tuber and root-crop-based systems. Singh *et al.* (2021) [46] observed a decline in available soil K and negative apparent K balances under potato-based cropping systems in the Trans-Gangetic Plains of India. Similarly, Sharma *et al.* (2002) [47] reported negative K balances in rice-based cropping systems involving potato, which was attributed to substantial crop removal and inadequate K replenishment. Zhao *et al.* (2025) [48] also reported K deficits under certain NPK regimes in sweet potato, demonstrating the potential for negative K balances in storage-root cropping systems.

Table 7. Net gain or loss of nitrogen in soil after harvest of yam bean as influenced by biofertilizers and inorganic fertilizers

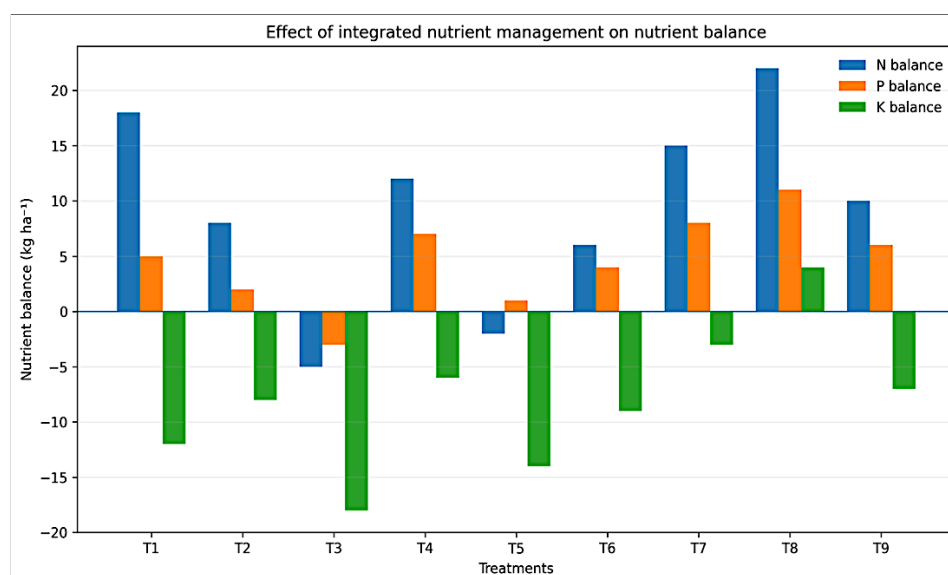
Tr. No.	Treatment details	Initial nitrogen status (kg ha ⁻¹)	Nitrogen added (kg ha ⁻¹)	Total available nitrogen (kg ha ⁻¹)	Nitrogen uptake (kg ha ⁻¹)	Expected Nitrogen balance (kg ha ⁻¹)	Actual nitrogen balance at harvest (kg ha ⁻¹)	Net gain or loss of N (kg ha ⁻¹)
T ₁	Control	218.32	0	218.32	10.76	207.56	235.24	27.68
T ₂	VC @ 5.0 t ha ⁻¹ + RDF (80:40:100 NPK kg ha ⁻¹) (P through SSP)	218.32	155	373.32	16.68	356.64	263.91	-92.73
T ₃	VC @ 5.0 t ha ⁻¹ + RDF (P through Rock Phosphate)	218.32	155	373.32	23.40	349.92	279.10	-70.82
T ₄	VC @ 5.0 t ha ⁻¹ + RDF (P through Basic slag)	218.32	155	373.32	27.34	345.98	286.42	-59.56
T ₅	VC @ 5.0 t ha ⁻¹ + RDF (N through KAB)	218.32	153	371.32	19.68	351.64	277.25	-74.39
T ₆	VC @ 7.5 t ha ⁻¹ + RDF (P through SSP) + Azotobacter + VAM	218.32	192.5	410.82	33.43	377.39	299.89	-77.50
T ₇	VC @ 7.5 t ha ⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM	218.32	192.5	410.82	43.26	367.56	310.88	-56.68

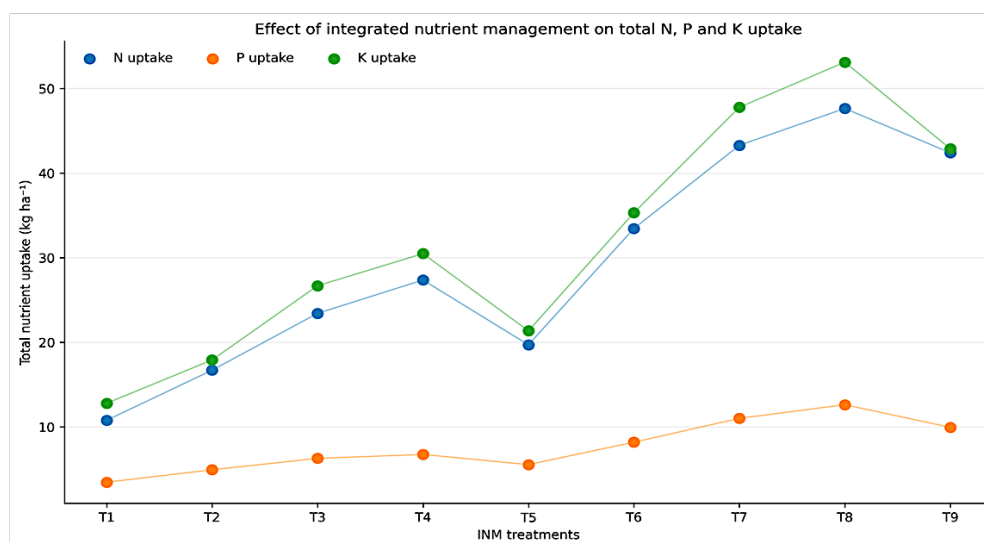
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Tr. No.	Treatment details	Initial nitrogen status (kg ha ⁻¹)	Nitrogen added (kg ha ⁻¹)	Total available nitrogen (kg ha ⁻¹)	Nitrogen uptake (kg ha ⁻¹)	Expected Nitrogen balance (kg ha ⁻¹)	Actual nitrogen balance at harvest (kg ha ⁻¹)	Net gain or loss of N (kg ha ⁻¹)
T ₈	VC @ 7.5 t ha ⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM	218.32	192.5	410.82	47.62	363.20	312.06	-51.14
T ₉	VC @ 7.5 t ha ⁻¹ + RDF (N through KAB) + Azotobacter + VAM	218.32	190.5	408.82	42.38	366.44	304.08	-62.36
	Mean	218.32	154	372.32	29.39	342.92	285.42	-57.5

Table 8. Net gain or loss of phosphorus in soil after harvest of yam bean as influenced by biofertilizers and inorganic fertilizers

Tr. No.	Treatment details	Initial phosphorus status (kg ha ⁻¹)	phosphorus added (kg ha ⁻¹)	Total available phosphorus (kg ha ⁻¹)	phosphorus uptake (kg ha ⁻¹)	Expected phosphorus balance (kg ha ⁻¹)	Actual phosphorus balance at harvest (kg ha ⁻¹)	Net gain or loss of P (kg ha ⁻¹)
T ₁	Control	10.29	0	10.29	3.44	6.85	8.40	1.55
T ₂	VC @ 5.0 t ha ⁻¹ + RDF (80:40:100 NPK kg ha ⁻¹) (P through SSP)	10.29	85	95.29	4.91	90.38	10.76	-79.62
T ₃	VC @ 5.0 t ha ⁻¹ + RDF (P through Rock Phosphate)	10.29	85	95.29	6.26	89.03	11.47	-77.56
T ₄	VC @ 5.0 t ha ⁻¹ + RDF (P through Basic slag)	10.29	85	95.29	6.72	88.57	11.74	-76.83
T ₅	VC @ 5.0 t ha ⁻¹ + RDF (N through KAB)	10.29	77	87.29	5.52	81.77	11.20	-70.57
T ₆	VC @ 7.5 t ha ⁻¹ + RDF (P through SSP) + Azotobacter + VAM	10.29	107.5	117.79	8.17	109.62	11.95	-97.67
T ₇	VC @ 7.5 t ha ⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM	10.29	107.5	117.79	10.99	106.62	12.73	-94.07
T ₈	VC @ 7.5 t ha ⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM	10.29	107.5	117.79	12.60	105.19	12.95	-92.24
T ₉	VC @ 7.5 t ha ⁻¹ + RDF (N through KAB) + Azotobacter + VAM	10.29	99.5	109.79	9.93	99.86	12.34	-87.52
	Mean	10.29	83.77	94.06	7.61	86.45	11.50	-74.94

Observation table:



T₁ = Control; T₂ = VC @ 5.0 t ha⁻¹ + RDF (80:40:100 NPK kg ha⁻¹) (P through SSP); T₃ = VC @ 5.0 t ha⁻¹ + RDF (P through Rock Phosphate); T₄ = VC @ 5.0 t ha⁻¹ + RDF (P through Basic slag); T₅ = VC @ 5.0 t ha⁻¹ + RDF (N through KAB); T₆ = VC @ 7.5 t ha⁻¹ +

RDF (P through SSP) + Azotobacter + VAM; T₇ = VC @ 7.5 t ha⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM; T₈ = VC @ 7.5 t ha⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM; T₉ = VC @ 7.5 t ha⁻¹ + RDF (N through KAB) + Azotobacter + VAM.

Table 9. Net gain or loss of potassium in soil after harvest of yam bean as influenced by biofertilizers and inorganic fertilizers

Tr. No.	Treatment details	Initial potassium status (kg ha ⁻¹)	potassium added (kg ha ⁻¹)	Total available potassium (kg ha ⁻¹)	potassium uptake (kg ha ⁻¹)	Expected potassium balance (kg ha ⁻¹)	Actual potassium balance at harvest (kg ha ⁻¹)	Net gain or loss of K (kg ha ⁻¹)
T ₁	Control	205.68	0	205.68	12.77	192.91	175.80	-17.11
T ₂	VC @ 5.0 t ha ⁻¹ + RDF (80:40:100 NPK kg ha ⁻¹) (P through SSP)	205.68	160	365.68	17.89	347.79	212.57	-135.22
T ₃	VC @ 5.0 t ha ⁻¹ + RDF (P through Rock Phosphate)	205.68	160	365.68	26.66	339.02	254.03	-84.99
T ₄	VC @ 5.0 t ha ⁻¹ + RDF (P through Basic slag)	205.68	160	365.68	30.46	335.22	261.41	-73.81
T ₅	VC @ 5.0 t ha ⁻¹ + RDF (N through KAB)	205.68	74	279.68	21.33	258.35	247.09	-11.26
T ₆	VC @ 7.5 t ha ⁻¹ + RDF (P through SSP) + Azotobacter + VAM	205.68	190	395.68	35.29	360.39	261.82	-98.57
T ₇	VC @ 7.5 t ha ⁻¹ + RDF (P through Rock Phosphate) + Azotobacter + VAM	205.68	190	395.68	47.75	347.93	275.97	-71.96
T ₈	VC @ 7.5 t ha ⁻¹ + RDF (P through Basic slag) + Azotobacter + VAM	205.68	190	395.68	53.09	342.59	280.74	-61.85
T ₉	VC @ 7.5 t ha ⁻¹ + RDF (N through KAB) + Azotobacter + VAM	205.68	104	309.68	42.86	266.82	262.73	-4.09
	Mean	205.68	136.44	342.12	32.01	310.11	248.01	-62.09

Conclusion

The present study demonstrated that integrated nutrient management significantly influenced soil–plant nutrient dynamics, nutrient uptake, soil chemical properties and biological activity of yam bean grown in lateritic soil conditions of Konkan. Among the nutrient management treatments, the application of vermicompost @ 7.5 t ha⁻¹ + RDF with phosphorus through basic slag + Azotobacter + VAM (T₈) consistently resulted in superior soil fertility and biological responses.

Treatment T₈ maintained comparatively higher soil pH and organic carbon and recorded the highest available N, P₂O₅ and K₂O as well as DTPA-extractable Fe, Mn, Zn and Cu at harvest. It also enhanced soil microbial populations and enzymatic activities, indicating improved biological functioning and nutrient cycling under integrated nutrient management.

The improved soil nutrient availability under T₈ was reflected in greater nutrient acquisition by yam bean. Total N, P and K uptake reached 47.62, 12.60 and 53.09 kg ha⁻¹, respectively, indicating en

hanced nutrient-use efficiency associated with the combined application of higher vermicompost, basic slag and biofertilizers. The increased microbial population and activities of urease, dehydrogenase, acid phosphatase and alkaline phosphatase further indicated that integration of organic, inorganic and biological nutrient sources stimulated nutrient transformation and biological activity in the rhizosphere.

However, the apparent nutrient balance revealed negative *N*, *P* and *K* balances in all fertilized treatments, including *T*₈, with net balances of -51.14, -92.24 and -61.85 kg ha⁻¹, respectively. This indicates that although integrated nutrient management improved nutrient availability and crop nutrient uptake during the season, nutrient replenishment needs to be carefully considered for maintaining long-term soil fertility, particularly under the high-rainfall conditions of lateritic soils.

Overall, the integration of vermicompost @ 7.5 t ha⁻¹, RDF with phosphorus through basic slag, Azotobacter and VAM (*T*₈) proved effective in improving soil nutrient availability, micronutrient status, plant nutrient uptake and soil biological activity of yam bean under the experimental conditions. The results highlight the potential of combining organic, inorganic and biological nutrient sources for improving nutrient cycling and soil fertility in lateritic soils of Konkan.

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