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Sustainable Soil Management through Organic Amendments and Legume Inclusion in Intensive Sudan Grass Cropping Systems

Deo Narayan Singh [a++*], Jitendra Singh Bohra [b#], Gaurav [a++], Tejbal Singh [b†] and Ajay Kumar [b†]

[a] Department of Agronomy, Udai Pratap College, Varanasi – 221002, India.
[b] Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi – 221005, India.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

The study evaluated the effects of fertility levels, organic nitrogen sources, and cropping sequences on soil physico-chemical and biological properties in a Sudan grass-based forage system on Gangetic alluvial soils at Varanasi, India, during 2015–16 and 2016–17. A split-plot design with three replications was employed, comprising two fertility levels (100% and 75% recommended dose of fertilizers, RDF) integrated with four organic nitrogen sources (20 and 40 kg N ha^{-1} through farmyard manure or vermicompost) in the main plots, and three cropping sequences (Sudan grass–Berseem, Sudan grass–oats, Sudan grass–barley) in the subplots. Soil pH, electrical conductivity,

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[++] *Assistant Professor;* [#] *Professor;* [†] *Research Scholar;*
**Corresponding author: E-mail: sdeonarayan@gmail.com, 0000-0001-7870-6722;*

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and organic carbon remained statistically unaffected by fertility levels, organic sources, and cropping sequences over the two-year period, reflecting the buffering capacity of the alluvial soil and the short experimental duration. In contrast, soil microbial biomass carbon (SMBC) and available macronutrients (N, P, K) and sulfur responded significantly to organic nitrogen sources, with 40 kg N ha^{-1} through vermicompost consistently recording the highest SMBC (171.4 and 186.2 µg g^{-1}) and available NPKS relative to lower organic doses and farmyard manure. Reducing mineral fertilizer from 100% to 75% RDF did not significantly affect SMBC or available N, K, and S, though available P was slightly but significantly higher under 100% RDF in both years. The Sudan grass–Berseem sequence produced significantly higher available soil N and, in the second year, higher SMBC than cereal-based sequences, indicating the beneficial role of legume inclusion in nitrogen enrichment and stimulation of soil microbial activity. Overall, the results demonstrate that integrating reduced mineral fertilizer rates with higher doses of vermicompost, coupled with Sudan grass–Berseem rotation, can enhance soil biological health and nutrient availability without compromising key chemical properties in alluvial soils under intensive forage production. However, the observed trends in soil organic carbon and biological properties reflect short-term responses, and longer-term field experiments are required to confirm sustained soil carbon sequestration and long-term sustainability outcomes.

Keywords: Sudan grass; fodder-based cropping systems; soil health; soil microbial biomass carbon.

1. Introduction

Livestock rearing is an integral component of the agricultural economy in India, providing livelihood security to nearly two-thirds of the rural community. However, the sector faces a critical constraint in the form of a severe feed and fodder deficit. Recent estimates indicate a net deficiency of approximately 30.65% in green fodder and 11.85% in dry fodder across the country, with projections suggesting a deficit of over 335 million tonnes in green fodder by 2030 (Manasa et al., 2024; Singh et al., 2022). To bridge this widening demand-supply gap, intensive cultivation of high-yielding forage crops like Sudan grass (*Sorghum sudanense*) has become imperative. Sudan grass, a multi-cut summer forage, is highly valued for its quick growth, high biomass potential, and adaptability (Acevedo et al., 2019; Ayyangar & Ponnaiya, 1938). To realize the yield potential of such heavy-feeding forage crops, farmers often resort to indiscriminate application of chemical fertilizers. While this practice may boost short-term productivity, it has precipitated a severe crisis in soil health. A comprehensive study by the Indian Council of Agricultural Research (ICAR) covering 2017–2023 revealed that nearly 44% of India's cultivated soils are deficient in organic carbon, with levels plummeting from 2–3% to a critical 0.4–0.7% over the last seven decades (Nayer, 2025). Continuous reliance on inorganic fertilizers, particularly nitrogenous sources, has been linked to soil acidification, destruction of soil aggregate structure, and a significant reduction in microbial diversity and functional redundancy (Pahalvi et al., 2021).

In this context, Integrated Nutrient Management (INM) has emerged as a sustainable strategy to restore soil vitality without compromising crop productivity. The synergistic use of organic manures and inorganic fertilizers not only improves soil physico-chemical properties but also enhances nutrient use efficiency (Paramesh et al., 2023). Among organic amendments, farmyard manure (FYM) and vermicompost are widely utilized. However, vermicompost is increasingly recognized as superior due to its lower C:N ratio, higher microbial load, and accelerated mineralization rate compared to conventional FYM (Chiranjeeb et al., 2020; Garnaik et al., 2024). Research indicates that vermicompost amendment can significantly enhance soil microbial biomass carbon (SMBC) and enzyme activities, which are sensitive indicators of soil biological health (Abbas et al., 2024).

Furthermore, the sustainability of forage production systems is heavily influenced by the cropping sequence. Monocropping or cereal-cereal rotations often lead to nutrient mining and pest buildup. Diversifying cropping systems by including leguminous fodder crops like Berseem (*Trifolium alexandrinum*) can interrupt these negative trends. Legumes contribute to the system through symbiotic nitrogen fixation—estimated at 100–400 kg N ha^{-1} $year^{-1}$ for Berseem—and by improving soil structure through their deep root systems (Kebede, 2021;

Raza et al., 2020). The "rhizodeposition" of nitrogen and carbon by legumes benefits the succeeding crops and stimulates the soil microbiome (Domnariu et al., 2024).

Despite the individual benefits of these management practices being known, there is a paucity of comprehensive information on their interactive effects in alluvial soils, particularly regarding the trade-offs between reducing chemical fertilizer doses and supplementing with different organic nitrogen sources under varying cropping sequences. Therefore, the present investigation was undertaken to evaluate the effect of fertility levels, organic nitrogen sources, and cropping sequences on soil physico-chemical properties, microbial biomass, and nutrient availability in a Sudan grass-based cropping system.

2. Materials and Methods

The field experiment was conducted during the 2015–16 and 2016–17 cropping seasons at the Agricultural Research Farm, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi, Uttar Pradesh, India (25°15′19.7″ N, 82°59′34.2″ E; 76 m amsl), on Gangetic alluvial soils classified as Inceptisols. The climate is semi-arid to sub-humid with mean annual rainfall >1100 mm, predominantly received during the monsoon (mid-June to September). Prior to initiation of the experiment, composite surface soil samples (0–20 cm) were collected, air-dried, crushed, and passed through a 2 mm sieve for characterization. The soil was sandy clay loam with pH 7.2 determined using a glass-electrode pH meter (Jackson, 1973), organic carbon 0.34% by the Walkley and Black rapid titration method (Walkley & Black, 1934), available N 198.6 kg ha^{-1} by the alkaline $KMnO_4$ method (Subbiah & Asija, 1956), available P_2O_5 18.59 kg ha^{-1} by Olsen's 0.5 N $NaHCO_3$ extraction (Olsen et al., 1954), and available K_2O 180.5 kg ha^{-1} by flame photometry (Jackson, 1973). The experiment was laid out in a split-plot design with three replications. Main plots comprised eight nutrient management combinations in kharif Sudan grass based on two fertility levels (100% and 75% of recommended dose of fertilizer, RDF: 120 kg N + 60 kg P_2O_5 + 60 kg K_2O ha^{-1}) integrated with organic sources supplying 20 or 40 kg N ha^{-1} through farmyard manure (FYM) or vermicompost. Subplots consisted of three cropping sequences: Sudan grass–berseem, Sudan grass–barley, and Sudan grass–oats. Organic manures were analyzed for nutrient content on an oven-dry basis and their application rates were adjusted for moisture content, with FYM containing about 0.48–0.49% N and vermicompost 1.14–1.16% N in the two years. FYM and vermicompost were uniformly incorporated into the soil 10 days before sowing Sudan grass, while full doses of P and K and one-fourth of the mineral N were applied basally; the remaining N was top-dressed in three equal splits at 30 days after sowing and after first and second cuttings of Sudan grass.

For soil health assessment, post-harvest soil samples (0–20 cm) were collected from each plot after completion of the cropping sequence in both years. Samples for physico-chemical analysis were air-dried and sieved (2 mm), whereas a sub-sample for biological parameters was kept at field moisture in sealed polythene bags and stored at low temperature until analysis (Cochran & Cox, 1957). Soil pH and electrical conductivity (EC) of 1:2.5 soil–water suspensions were determined using a digital pH meter and conductivity meter, respectively (Jackson, 1973). Soil organic carbon was estimated by the Walkley and Black wet oxidation method (Walkley & Black, 1934), and available N, P, K, and S were determined using the same standard methods as in the initial characterization (alkaline $KMnO_4$ for N, Olsen's $NaHCO_3$ extraction for P, flame photometry for K, and a standard turbidimetric/photometric procedure for sulfate-S, as per the laboratory protocol). Soil microbial biomass carbon (SMBC) was measured using the chloroform fumigation–extraction method, with extraction in 0.5 M K_2SO_4 and conversion using an appropriate kEC factor (Vance et al., 1987).

All soil data were subjected to analysis of variance (ANOVA) for split-plot design following standard procedures (Cochran & Cox, 1957; Gomez & Gomez, 1984). Treatment means were compared using the critical difference (CD) at the 5% probability level, and statistical analysis was carried out separately for each year; where error variances were homogeneous, a pooled analysis over years was performed.

3. Results

The soil physico-chemical and biological properties as influenced by fertility levels, organic sources of nitrogen, and cropping sequences are presented in Table 1. The initial soil analysis before the start of the experiment indicated a neutral reaction and non-saline condition with a pH of 7.38, EC of 0.342 dS m^{-1}, organic carbon content of 0.336%, and soil microbial biomass carbon (SMBC) of 158.6 µg g^{-1}, characteristic of alluvial soils of the experimental site.

3.1 Soil pH and Electrical Conductivity

Soil pH was not significantly affected by fertility levels, organic nitrogen sources, or cropping sequences during either 2015–16 or 2016–17, with values remaining close to the initial pH of 7.38 across treatments. Similarly, soil electrical conductivity (EC) showed no significant variation among the treatments in both years, and EC values remained low (around 0.34–0.35 dS m^{-1}), indicating that neither mineral fertilizers nor organic amendments nor cropping sequences induced any salinity build-up in the soil during the experimental period.

3.2 Soil Organic Carbon

Soil organic carbon content exhibited only marginal numerical differences among treatments and years, and these differences were statistically non-significant for fertility levels, organic sources, and cropping sequences in both 2015–16 and 2016–17. Although slightly higher organic carbon values were observed under treatments receiving higher doses of organic sources, particularly 40 kg N through vermicompost, the short duration of the study (two years) was insufficient to cause statistically significant accumulation of stable soil organic carbon pools.

3.3 Soil Microbial Biomass Carbon (SMBC)

In contrast to the chemical properties, SMBC responded markedly to organic nitrogen sources and cropping sequence, while fertility level (100% vs. 75% RDF) had no significant effect in either year. Reduction of fertilizer dose from 100% to 75% RDF did not significantly decrease SMBC, indicating that a 25% reduction in mineral fertilizer could be achieved without adverse impact on microbial biomass under the given management conditions. Among organic nitrogen sources, application of 40 kg N through vermicompost (O_4) recorded the highest SMBC values (171.4 and 186.2 µg g^{-1} in 2015–16 and 2016–17, respectively), which were significantly superior to 20 kg N through FYM (O_1) and 20 kg N through vermicompost (O_2), and at par or superior to 40 kg N through FYM (O_3). The higher rate (40 kg N ha^{-1}) of organic nitrogen consistently enhanced SMBC compared to the lower rate (20 kg N ha^{-1}), suggesting increased supply of organic substrates and improved habitat conditions for soil microorganisms under heavier organic loading. Cropping sequences did not significantly influence SMBC in 2015–16; however, a significant effect emerged in 2016–17, with the Sudan grass–Berseem sequence (S_1) recording the highest SMBC (182.7 µg g^{-1}), which was significantly higher than Sudan grass–Oats (S_2) and Sudan grass–Barley (S_3). The inclusion of Berseem, a leguminous fodder, in the sequence likely contributed to higher microbial activity through biological nitrogen fixation and more favorable root exudation patterns compared to the cereal-based sequences with Oats and Barley.

Available NPK, S (Kg ha^{-1}): The status of available macronutrients (N, P, K) and sulphur in soil as influenced by fertility levels, organic manures applied to *kharif* Sudan grass, and cropping sequences after harvest of the crop is presented in Table 2. The initial soil analysis indicated available N, P, K and S contents of 197.1, 18.35, 180.85 and 17.86 kg ha^{-1}, respectively, reflecting moderate fertility typical of alluvial soils at the experimental site.

Effect of fertility levels: Fertility levels (100% and 75% RDF) did not significantly affect available N, K, or S in either 2015–16 or 2016–17, and the values remained close to the initial status, suggesting that a 25% reduction in recommended fertilizer dose did not markedly deplete these nutrients in the short term. Available P, however, was significantly higher under 100% RDF than 75% RDF in both years, with 100% RDF recording 19.15 and 19.55 kg ha^{-1} compared to 18.42 and 18.47 kg ha^{-1} under 75% RDF in 2015–16 and 2016–17, respectively.

Effect of organic nitrogen sources: Application of nitrogen through organic sources significantly influenced available N, P, K and S in soil after harvest in both years. The highest values of available N, P, K and S were consistently recorded with 40 kg N through vermicompost (O_4), which registered 209.4 and 212.9 kg ha^{-1} N, 19.39 and 19.69 kg ha^{-1} P, 189.8 and 191.5 kg ha^{-1} K, and 17.82 and 18.07 kg ha^{-1} S during 2015–16 and 2016–17, respectively, and these were significantly superior to 20 kg N through FYM (O_1) and 20 kg N through vermicompost (O_2), and higher than or at par with 40 kg N through FYM (O_3).

Table 1. Effect of fertility levels, organic manures applied in *Kharif* sudan grass, and cropping sequences on soil health parameters after harvest of the crop

	Soil pH		**EC (dsm^{-1})**		**Organic Carbon (%)**		**SMBC (µg/g)**	
Initial Value (Before start of the Experiment)	**7.38**		**0.342**		**0.336**		**158.6**	
	2015-16	**2016-17**	**2015-16**	**2016-17**	**2015-16**	**2016-17**	**2015-16**	**2016-17**
Fertility Levels								
100% RDF (F_1)	7.34	7.39	0.354	0.345	0.343	0.344	161.0	174.2
75% RDF (F_2)	7.34	7.28	0.344	0.346	0.347	0.346	156.5	171.6
SEm±	0.06	0.06	0.003	0.004	0.004	0.004	1.90	2.58
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Nitrogen through organic sources								
20 kg N through FYM (O_1)	7.30	7.33	0.350	0.335	0.333	0.339	147.4^{c}	163.9^{c}
20 kg N through Vermicompost (O_2)	7.35	7.34	0.352	0.344	0.341	0.343	151.1^{c}	163.6^{c}
40 kg N through FYM (O_3)	7.35	7.30	0.342	0.349	0.349	0.347	165.2^{ab}	177.8^{b}
40 kg N through Vermicompost (O_4)	7.35	7.35	0.350	0.353	0.356	0.352	**171.4^{a}**	**186.2^{a}**
SEm±	0.08	0.09	0.00	0.01	0.01	0.01	2.69	3.65
CD (P=0.05)	NS	NS	NS	NS	NS	NS	8.16	11.08
Cropping sequences								
Sudan grass – Berseem (S_1)	7.33	7.33	0.353	0.349	0.351	0.349	160.7	**182.7^{a}**
Sudan grass – Oats (S_2)	7.29	7.29	0.349	0.345	0.344	0.347	158.9	168.7^{b}
Sudan grass – Barley (S_3)	7.39	7.38	0.344	0.342	0.340	0.339	156.7	167.3^{b}
SEm±	0.06	0.05	0.00	0.00	0.00	0.00	1.78	2.07
CD (P=0.05)	NS	NS	NS	NS	NS	NS	NS	5.96

Table 2. Effect of fertility levels, organic manures applied in *Kharif* sudan grass, and cropping sequences on available NPK, S (Kg ha^{-1}) in soil after harvest of the Crop

	Available N		**Available P**		**Available K**		**Available S**	
Initial Value (Before start of the Experiment)	**197.1**		**18.35**		**180.85**		**17.86**	
	2015-16	**2016-17**	**2015-16**	**2016-17**	**2015-16**	**2016-17**	**2015-16**	**2016-17**
Fertility Levels								
100% RDF (F$_1$)	201.8	207.0	**19.15^{a}**	**19.55^{a}**	183.0	184.4	17.06	17.38
75% RDF (F$_2$)	198.3	201.0	18.42^{b}	18.47^{b}	179.1	180.5	16.56	16.76
SEm±	2.66	2.43	0.20	0.20	1.70	1.85	0.20	0.25
CD (*P*=0.05)	NS	NS	0.62	0.60	NS	NS	NS	NS
Nitrogen through organic sources								
20 kg N through FYM (O$_1$)	191.1^{c}	194.9^{c}	18.49^{b}	18.56^{b}	175.3^{c}	178.2^{c}	16.12^{b}	16.53^{b}
20 kg N through Vermicompost (O$_2$)	194.0^{c}	198.1^{c}	18.20^{b}	18.39^{b}	176.6^{c}	177.7^{c}	16.07^{b}	16.39^{b}
40 kg N through FYM (O$_3$)	205.7^{ab}	210.0^{ab}	19.05^{a}	19.39^{a}	182.4^{b}	182.4^{b}	17.23^{a}	17.28^{a}
40 kg N through Vermicompost (O$_4$)	**209.4^{a}**	**212.9^{a}**	**19.39^{a}**	**19.69^{a}**	**189.8^{a}**	**191.5^{a}**	**17.82^{a}**	**18.07^{a}**
SEm±	3.76	3.43	0.29	0.28	2.40	2.62	0.29	0.36
CD (*P*=0.05)	11.41	10.42	0.88	0.84	7.28	7.94	0.87	1.09
Cropping sequences								
Sudan grass – Berseem (S$_1$)	**211.8^{a}**	**222.7^{a}**	18.96	19.28	183.3	184.7	17.00	17.36
Sudan grass – Oats (S$_2$)	195.8^{ab}	195.8^{b}	18.75	18.92	180.3	182.4	16.84	17.00
Sudan grass – Barley (S$_3$)	192.5^{b}	193.5^{b}	18.6	18.8	179.6	180.2	16.59	16.86
SEm±	3.36	3.07	0.15	0.14	1.63	1.82	0.19	0.20
CD (*P*=0.05)	9.68	8.83	NS	NS	NS	NS	NS	NS

Treatments receiving 40 kg N ha⁻¹ through either FYM or vermicompost (O_3 and O_4) generally maintained higher available nutrient status than those receiving 20 kg N ha⁻¹, indicating a positive contribution of higher organic inputs to nutrient build-up or conservation in soil. The lowest available N, P, K, and S values were recorded in treatments with 20 kg N through FYM or vermicompost, suggesting that lower organic N rates may be insufficient to significantly enhance soil nutrient pools beyond the initial levels under the given conditions.

Effect of cropping sequences: Cropping sequences significantly affected available N but had no significant effect on available P, K, or S in either year. The Sudan grass–Berseem sequence (S_1) recorded the highest available N (211.8 and 222.7 kg ha⁻¹ in 2015–16 and 2016–17, respectively), which was significantly higher than Sudan grass–Barley (S_3) in both years and higher than or comparable to Sudan grass–Oats (S_2). The inclusion of Berseem, a leguminous fodder, in the sequence likely contributed to build-up of available N through biological nitrogen fixation, reflected in the consistently higher soil N status under S_1 relative to the cereal-based sequences with Oats and Barley. Available P, K and S remained statistically similar across sequences, indicating that under the existing fertilizer and organic management, cropping sequence effects on these nutrients were less pronounced in the short term.

4. Discussion

The present investigation evaluated the integrated effects of fertility levels, organic nitrogen sources, and cropping sequences on soil health and nutrient dynamics in alluvial soils under forage-based cropping systems. The results demonstrate differential responses of soil properties to management interventions, with biological indicators proving more sensitive to short-term management changes than chemical properties.

4.1 Stability of Soil pH, EC, and Organic Carbon under Integrated Management

The non-significant effect of fertility levels, organic nitrogen sources, and cropping sequences on soil pH and electrical conductivity (EC) during the two-year study period indicates the buffering capacity of alluvial soils and the moderate nature of the amendments applied. Similar findings have been reported by (Dong et al., 2022), who observed no significant differences in soil EC (0.26–0.31 dS m⁻¹) and pH (7.89–8.43) among organic-amended soils and control treatments in short-term studies. The neutral to slightly alkaline pH range maintained across treatments suggests that neither acidification from nitrogen mineralization nor alkalinity from organic amendment application was pronounced enough to alter soil reaction significantly over the experimental duration (Ozlu & Kumar, 2018). While long-term studies have documented pH decline and EC increase with continuous organic manure application (Abbas et al., 2024), the present study's relatively short duration (two years) and moderate application rates likely prevented detectable changes in these stable soil properties. (Villafuerte et al., 2024) similarly noted that short-term biochar and compost additions did not significantly influence pH in alkaline soils. The maintenance of stable pH is agronomically desirable, as it ensures consistent nutrient availability and prevents aluminum or manganese toxicity that could occur under acidification.

The lack of significant increase in soil organic carbon (SOC) content over the two-year period, despite numerical increases particularly under higher vermicompost rates, reflects the slow turnover of stable organic carbon pools in alluvial soils. Organic carbon accumulation is a gradual process, with detectable changes typically requiring 5–10 years of continuous organic inputs (Kumari et al., 2024). (Kraut-Cohen et al., 2023) demonstrated that long-term compost application elevated soil organic matter content, but short-term effects were primarily observed in microbial biomass and enzyme activities rather than total organic carbon. The initial organic carbon content of 0.336% in the experimental soil was relatively low, and the amounts of organic amendments applied (20 and 40 kg N ha⁻¹) may have been insufficient to produce statistically significant increases in the stable carbon pool within the short experimental timeframe (Ozlu & Kumar, 2018). It is therefore important to interpret the observed SOC trends cautiously, as measurable changes in stable carbon pools typically require longer experimental durations. Long-term trials are essential to ascertain whether repeated application of vermicompost and legume inclusion can lead to sustained soil carbon sequestration in alluvial soils.

4.2 Superior Impact of Vermicompost on Soil Microbial Biomass Carbon

In contrast to the chemical properties, soil microbial biomass carbon (SMBC) exhibited marked sensitivity to organic nitrogen sources, with 40 kg N through vermicompost consistently producing the highest SMBC values in both years. This finding aligns with extensive literature documenting the superior quality of vermicompost compared to farmyard manure (FYM) in stimulating soil biological activity (Chiranjeeb et al., 2020). The enhanced microbial biomass under vermicompost treatment can be attributed to several factors: (i) accelerated mineralization of organic matter during vermicomposting produces more readily available substrates for microbial growth (Tognetti et al., 2005); (ii) vermicompost contains higher concentrations of nutrients, particularly phosphorus and total organic carbon, compared to FYM (Suthar, 2009); and (iii) the presence of beneficial microorganisms and plant growth-promoting substances in vermicompost creates a favorable environment for microbial proliferation (Oyege & Balaji Bhaskar, 2023).

Studies confirmed that vermicompost showed better nutrient and microbial properties than farmyard manure, resulting in higher soil microbial counts. The significant increase in SMBC from 158.6 µg g^{-1} (initial) to 186.2 µg g^{-1} under 40 kg N through vermicompost represents a 17.4% improvement, which is consistent with reported increases of 28.7–47% in long-term studies (Abbas et al., 2024). The dose-dependent response, with 40 kg N consistently outperforming 20 kg N regardless of source, underscores the importance of adequate organic substrate availability for sustaining soil microbial populations (Chiranjeeb et al., 2020).

The comparable or slightly inferior performance of 40 kg N through FYM relative to vermicompost may be explained by the slower decomposition rate and lower nutrient concentration of FYM (Tognetti et al., 2005). Vermicompost has a narrower C:N ratio and higher proportion of humic substances, which facilitate more rapid nutrient release and microbial colonization (Bairwa et al., 2021). Nevertheless, both FYM and vermicompost at higher rates (40 kg N) significantly enhanced SMBC compared to lower rates, indicating that quantity of organic input is a critical determinant of microbial biomass alongside quality (Liu et al., 2009). Higher soil microbial biomass carbon serves as an active reservoir of nutrients and plays a pivotal role in regulating nutrient cycling through immobilization–mineralization processes. Enhanced SMBC under vermicompost application likely improved synchronization between nutrient release and crop demand, thereby contributing to higher available N, P, K, and S observed in this study (Chiranjeeb et al., 2020; Oyege & Balaji Bhaskar, 2023). Moreover, a biologically active soil is better equipped to buffer against environmental stresses, improve soil structure, and sustain forage productivity under intensive cutting regimes, thereby enhancing overall ecosystem resilience.

4.3 Enhanced Nutrient Availability through Organic Nitrogen Sources

The significant influence of organic nitrogen sources on available N, P, K, and S in soil demonstrates the multifunctional role of organic amendments beyond simple nitrogen supply. Consistent with its positive effect on microbial biomass, application of 40 kg N through vermicompost also resulted in higher availability of N, P, K, and S, reflecting improved mineralization and nutrient cycling processes (Kumari et al., 2024). Organic manures promote nutrient availability through several mechanisms: (i) production of organic acids during decomposition that solubilize bound phosphorus and potassium (Ozlu & Kumar, 2018); (ii) reduction of phosphorus fixation through formation of organic-phosphate complexes and chelation of calcium ions (Bairwa et al., 2021); (iii) enhanced microbial activity that accelerates mineralization of organic nitrogen, phosphorus, and sulfur (Grzyb et al., 2020); and (iv) improved soil physical properties that facilitate root exploration and nutrient uptake (Suthar, 2009).

The increase in available phosphorus under organic treatments is particularly significant given that phosphorus fixation is a major constraint in many agricultural soils. Studies have consistently shown that vermicompost and FYM reduce phosphorus fixation and improve phosphorus availability by modifying soil pH, releasing chelating agents, and blocking phosphorus adsorption sites (Bairwa et al., 2021). The earthworm-mediated transformation of organic phosphorus into plant-available orthophosphate during vermicompost production further contributes to enhanced phosphorus availability (Tognetti et al., 2005).

Similarly, the higher available potassium under vermicompost treatment results from both direct addition and enhanced solubilization of native potassium reserves. Organic acids released during organic matter decomposition can dissolve feldspar and mica minerals, releasing bound potassium into available forms (Navi et al., 2025). The continuous release of nutrients from organic amendments provides sustained nutrient availability throughout the crop growth period, unlike chemical fertilizers which may be subject to rapid leaching or fixation (Kumari et al., 2024).

The significant response of available sulfur to organic nitrogen sources, with highest values under 40 kg N through vermicompost, indicates that organic amendments serve as important sulfur sources in addition to NPK (Navi et al., 2025). The mineralization of organic sulfur by microbial populations converts organically bound sulfur into plant-available sulfate form (Navi et al., 2025). Given the increasing recognition of sulfur deficiency in intensive cropping systems, the sulfur-supplying capacity of organic amendments represents an additional benefit of integrated nutrient management.

4.4 Legume-Mediated Nitrogen Enrichment in Cropping Sequences

The significantly higher available nitrogen content in soil following the Sudan grass–Berseem sequence compared to cereal-based sequences underscores the nitrogen-fixing capacity of leguminous forages and their role in building soil fertility (Frey & Scheupp, 1992). Berseem clover (*Trifolium alexandrinum*) forms symbiotic associations with *Rhizobium* bacteria, capable of fixing atmospheric nitrogen at rates ranging from 100–400 kg N ha^{-1} $year^{-1}$ under favorable conditions (Kebede, 2021; Raza et al., 2020). The substantial nitrogen fixation capacity of Berseem contributes to enhanced soil nitrogen availability through multiple pathways: (i) direct addition of fixed nitrogen through root exudates and nodule senescence during crop growth (Frey & Scheupp, 1992); (ii) mineralization of nitrogen-rich residues and root biomass following crop termination (Salama, 2020); and (iii) stimulation of soil microbial nitrogen cycling processes in the rhizosphere of legumes (Liu et al., 2009). While Berseem inclusion significantly enhanced soil nitrogen through biological fixation and rhizodeposition, its influence on phosphorus, potassium, and sulfur was not detectable within the two-year timeframe. This may be due to strong soil buffering, relatively large native pools of P and K in alluvial soils, and the fact that legume-induced changes in non-nitrogen nutrients often manifest only under long-term rotations or residue recycling systems.

Jensen, (1996) revealed that a significant portion of total below-ground nitrogen in legumes is derived from root depositions, with rhizodeposits contributing to residual soil nitrogen. This "rhizodeposition effect" provides immediate nitrogen benefits to subsequent crops even before considering the decomposition of above-ground residues. The higher SMBC observed under Sudan grass–Berseem sequence in the second year (182.7 µg g^{-1}) further suggests that legume residues create favorable conditions for microbial proliferation, likely due to higher nitrogen content and more balanced C:N ratio compared to cereal residues (Domnariu et al., 2024).

5. Conclusion

The two-year field investigation in Sudan grass-based forage systems on Gangetic alluvial soils revealed short-term responses of soil biological and nutrient indicators to integrated nutrient management, while stable chemical properties such as soil organic carbon remained largely unchanged. However, biological and nutrient indicators were more responsive, with 40 kg N ha^{-1} through vermicompost markedly increasing soil microbial biomass carbon and available N, P, K, and S compared with lower organic doses and farmyard manure, while allowing a 25% reduction in mineral fertilizer without adverse effects on these parameters. The inclusion of Berseem in the Sudan grass–Berseem sequence further enhanced available soil nitrogen and SMBC relative to cereal-based rotations, underscoring the importance of legume integration for sustaining soil fertility in forage production systems. These findings suggest that combining 75% RDF with higher rates of vermicompost and legume-inclusive cropping sequences represents a promising strategy for improving soil biological health and nutrient availability while maintaining stable chemical properties in alluvial soils, thereby contributing to more sustainable and resilient fodder production.

From a practical perspective, the results indicate that farmers can reduce mineral fertilizer application by 25% without compromising soil biological health or nutrient availability by integrating vermicompost and legume-based rotations. Adoption of vermicompost, particularly at higher rates, may offer cost savings on chemical fertilizers while improving soil resilience, although its scalability will depend on local availability and on-farm composting capacity. Inclusion of Berseem in forage systems provides an additional low-cost strategy for enhancing soil nitrogen and sustaining productivity, making the proposed management approach suitable for resource-constrained and semi-intensive forage-based farming systems.

Disclaimer (Artificial Intelligence)

Artificial intelligence–based tools were used in a limited and responsible manner during the preparation of this manuscript. Specifically, selected AI-assisted platforms (e.g., Scispace and Perplexity) were employed to support literature discovery and to enhance language clarity and readability. All scientific interpretations, data analyses, critical discussions, and conclusions were conceived, verified, and finalized by the authors. The authors take full responsibility for the originality, accuracy, and integrity of the content presented in this manuscript.

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Competing Interests

Authors have declared that no competing interests exist.

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