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Assessment of Nutrient Dynamics under Integrated Application of Inorganic, Organic and Biofertilizers in Red Loam Soil

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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

Integrated nutrient management (INM) was evaluated through a 60-day incubation experiment using red loam soil to assess temporal changes in available nitrogen (N), phosphorus (P), potassium (K), and sulphur (S). Soil samples were incubated with combinations of recommended or soil test-based inorganic fertiliser, farmyard manure (FYM), and a biofertiliser consortium, with sampling at 15, 30, 45, and 60 days after incubation (DAI). The treatments produced distinct nutrient-release patterns over time. Available N generally increased up to 30 DAI under sole inorganic fertilisation, whereas treatments combining inorganic fertilisers

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with FYM and biofertilisers maintained the increase up to 45 DAI before a slight decline. Available P increased up to 45 DAI in most treatments and then declined at 60 DAI, with higher values under treatments integrating FYM and the biofertiliser consortium. Available K increased continuously throughout the 60-day incubation period, particularly under integrated treatments. Available S increased during the early-to-mid incubation period and was generally higher under integrated or soil test-based nutrient treatments than under the control, with treatment-dependent declines later in the incubation. Overall, combining inorganic, organic, and biological nutrient sources influenced the timing and persistence of nutrient availability in red loam soil. These findings characterise the time-dependent release of major nutrients under controlled incubation conditions.

Keywords: *Integrated nutrient management; red loam soil; nutrient availability; nitrogen; phosphorus; potassium; sulphur; farmyard manure; biofertiliser consortium; soil test-based NPK.*

1. Introduction

Integrated Nutrient Management (INM) has emerged as a pivotal strategy in modern agricultural practice, aiming to optimise the availability of essential nutrients for plant growth, enhance soil health, and ensure sustainable crop production. Among these essential nutrients, nitrogen (N), phosphorus (P), potassium (K), and sulphur (S) are primary contributors to plant growth and development. Understanding the intricate interplay between INM practices and the release of these vital nutrients in different soil types is crucial for achieving efficient nutrient utilisation, reducing environmental impacts, and sustaining agricultural productivity. Integrated nutrient management (INM) involves the use of different nutrient sources, such as organic manures, residues, and chemical fertilisers, to improve soil health and crop production. INM is important for marginal farmers who cannot afford to rely solely on chemical fertilisers. Organic manures and residues can improve soil structure and water retention while also supplying nutrients to crops. This can help reduce the need for chemical fertilisers and improve the sustainability of agricultural production. Integrated Nutrient Management involves the strategic integration of organic and inorganic fertilisers, along with other nutrient-enriching practices, to create a balanced and efficient nutrient supply system. This approach influences nutrient-release patterns and transformations within the soil matrix, thereby affecting nutrient availability to plants. Recent laboratory evidence from black clay soil indicates that the integrated application of mineral fertiliser, FYM, and a biofertiliser consortium can maintain nutrient availability for longer than the sole application of inorganic fertiliser, with distinct temporal responses for N, P, K, and S (Venkatesh *et al.*, 2024).

Sustainable agriculture relies on the careful management of organic matter in soil. Increasing soil organic matter content can help reverse soil degradation and improve soil fertility, which may lead to increased crop production (Weil and Magdoff, 2004). The interaction of organic materials with mineral particles in soil is a fundamental process that significantly affects soil organic matter (SOM) dynamics and the formation and stabilisation of soil aggregates (Golchin *et al.*, 1998).Evidence from irrigated wheat also indicates that integrated mineral, organic, and biological nutrient inputs can improve soil organic matter and nutrient status compared with conventional nutrient management (Hyder *et al.*, 2021).

Soil nutrient availability is a dynamic process influenced by numerous factors, including soil texture, structure, organic matter content, pH, and microbial activity. The effect of integrated nutrient management on N, P, K, and S release varies among soil types, each of which has unique physical and chemical properties that influence nutrient dynamics. Sandy soils, characterised by low nutrient-retention capacity, often experience rapid leaching of N, P, K, and S. INM practices can mitigate these losses by promoting gradual and controlled nutrient release, thereby improving nutrient-use efficiency. Conversely, clay-rich soils have a higher cation-exchange capacity, but they may exhibit nutrient immobilisation and reduced availability. INM interventions can stimulate microbial activity and promote nutrient mineralisation, thereby enhancing nutrient accessibility in such soils. Loam soils, with their balanced mixture of sand, silt, and clay, exhibit intermediate nutrient dynamics that can be further optimised through INM approaches. By elucidating nutrient interactions within the soil-plant system, nutrient utilisation can be optimised to support crop productivity and sustainable agricultural practices for a growing global population. Long-term studies further show that integrated organic and inorganic fertilisation can alter soil biological indicators associated with N mineralisation and improve soil nutrient status and nutrient transformations over time (Kumar *et al.*, 2024; Walia *et al.*, 2024).

Accordingly, a specific research gap addressed in this study is the characterisation of time-dependent N, P, K, and S release under combined inorganic fertiliser, FYM, and biofertiliser inputs in red loam soil during incubation.

Objective: The objective of this study was to assess the availability and release patterns of nitrogen, phosphorus, potassium, and sulphur in red loam soil under integrated applications of inorganic fertilisers, FYM, and a biofertiliser consortium during a 60-day incubation period.

2. Materials and Methods

An incubation experiment was conducted in the Department of Soil Science and Agricultural Chemistry, Agricultural College, Jagtial, to study the effect of integrated nutrient management on the availability and release patterns of nitrogen, phosphorus, potassium, and sulphur. Initially, 30 different soils were collected from mustard-growing fields in the Northern Telangana Zone and analysed for physico-chemical properties. Among them, three soils with varied physical and chemical properties were selected and collected in bulk for the incubation study. These soils were selected based on nutrient content, soil colour, and texture. The soils were collected at a depth of 0-15 cm, dried, processed using a wooden pestle and mortar, passed through a 2 mm sieve, and analysed to determine their physical and chemical properties. Approximately 1 kg of each soil sample was weighed into pots, subjected to the above treatments along with an absolute control, and incubated for 60 days while maintaining soil moisture at field capacity. Soil samples were collected at 15, 30, 45, and 60 days to determine physico-chemical properties and assess nutrient status and nutrient release following the integration of fertilisers with FYM (2.32 g kg^{-1} soil) and biofertilisers. The experiment was laid out in a completely randomised design (CRD) with three replications and included T1: 100% recommended dose of fertiliser (RDF), T2:

100% RDF + FYM, T3: 100% RDF + FYM + biofertiliser consortium, T4: 75% RDF, T5: 75% RDF + FYM, T6: 75% RDF + FYM + biofertiliser consortium, T7: soil test-based NPK, T8: 75% STB NPK + FYM, and T9: 75% STB NPK + FYM + biofertiliser consortium. The biofertiliser consortium included *Azotobacter* + phosphate-solubilising bacteria + potassium-solubilising bacteria + zinc-solubilising bacteria. The nutrient doses were 100% RDF (N:P:K - 26.8:17.9:17.9) mg kg^{-1}, 75% RDF (N:P:K - 20.1:13.4:13.4) mg kg^{-1}, STB (N:P:K - 34.8:17.9:17.9) mg kg^{-1}, and 75% STB NPK + FYM (N:P:K - 26.1:13.4:13.4) mg kg^{-1}. Analysis of the initial soil samples showed that the soil was loamy and red in colour, with available nitrogen, phosphorus, potassium, and sulphur contents of 67, 5.4, 75.9, and 9.0 mg kg^{-1}, respectively. Available nitrogen was estimated using the alkaline permanganate method (Subbiah and Asija, 1956); available phosphorus was determined using 0.5 M $NaHCO_3$ extraction (Olsen *et al.*, 1954); available potassium was determined using the neutral normal ammonium acetate method (Jackson, 1973); and available sulphur was determined using the method described by Williams and Steinbergs (1962).

Table 1. Amount of nutrients applied in Red loam soil in incubation study

Treatment	N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	FYM (g kg^{-1})
100% RDF	26.8	17.9	17.9	0
100% RDF+ FYM	26.8	17.9	17.9	2.32
100% RDF+ FYM+ BC	26.8	17.9	17.9	2.32
75 % RDF	20.1	13.4	13.4	0
75 % RDF + FYM	20.1	13.4	13.4	2.32
75 % RDF + FYM+ BC	20.1	13.4	13.4	2.32
STB NPK	34.8	17.9	17.9	0
75% STB NPK+FYM	26.1	13.4	13.4	2.32
75% STB NPK+FYM + BC	26.1	13.4	13.4	2.32
Control	0	0	0	0

Table 2. Details of the initial parameters in the soil

Sand (%)	Silt (%)	Clay (%)	pH	EC (dSm^{-1})	OC (%)	Available N (mg kg^{-1})	Available P (mg kg^{-1})	Available K (mg kg^{-1})	Available S (mg kg^{-1})
32.4	42.1	25.5	7.75	0.24	0.38	64.0	5.1	72.6	8.2

3. Results and Discussion

3.1 Available Nitrogen

In red loam soil, available nitrogen content at 15 DAI was significantly higher under STB NPK (79.5 mg kg^{-1} soil), which was on par with 75% STB NPK + FYM + biofertiliser consortium (79.0 mg kg^{-1} soil), 100% RDF + FYM + biofertiliser consortium (79.0 mg kg^{-1} soil), 100% RDF + FYM (78.3 mg kg^{-1} soil), 75% STB NPK + FYM (78.1 mg kg^{-1} soil), and 75% RDF + FYM + biofertiliser consortium (76.0 mg kg^{-1} soil). The higher amount of inorganic fertiliser received by the STB NPK treatment might have released more N into the soil. However, at 30 DAI, the 100% RDF + FYM + biofertiliser consortium treatment recorded the highest available N (85.3 mg kg^{-1} soil), followed by STB NPK (84.5 mg kg^{-1} soil), 75% STB NPK + FYM + biofertiliser consortium (83.5 mg kg^{-1} soil), 100% RDF + FYM (82.6 mg kg^{-1} soil), 75% STB NPK + FYM (80.8 mg kg^{-1} soil), 75% RDF + FYM + biofertiliser consortium (79.1 mg kg^{-1} soil), 100% RDF (77.7 mg kg^{-1} soil), 75% RDF + FYM (76.8 mg kg^{-1} soil), 75% RDF (75.5 mg kg^{-1} soil), and the control (66.5 mg kg^{-1} soil).

Table 3. Effect of integrated nutrient management on soil available nitrogen content (mg kg^{-1}) during incubation period in red loam soils

Treatment	15 DAI	30 DAI	45 DAI	60 DAI
100% RDF	72.3	77.7	76.8	74.2
100% RDF+ FYM	78.3	82.6	85.7	82.6
100% RDF+ FYM+ BC	79.0	85.3	85.9	83.5
75 % RDF	69.7	75.5	74.1	72.3
75 % RDF + FYM	70.6	76.8	79.9	76.5
75 % RDF + FYM+ BC	76.0	79.1	82.2	78.6
STB NPK	79.5	84.5	83.1	80.9
75% STB NPK+FYM	78.1	80.8	82.6	80.4
75% STB NPK+FYM + BC	79.0	83.5	86.6	84.4
Control	66.1	66.5	65.6	67.9
Mean	74.9	79.2	80.3	78.1
Sem±	2.47	2.08	3.00	2.81
CD (p=0.05)	5.50	4.63	6.68	6.26
CV	3.30	2.62	3.74	3.60

BC= Biofertilizer consortium, RDF= Recommended dose of fertilizer, STB NPK= Soil test based NPK

Under the 100% RDF + FYM + biofertiliser consortium treatment, the use of FYM and the biofertiliser consortium alongside inorganic fertilisers might have promoted mineralisation of organic N, biological N fixation, and the release of N from inorganic sources, resulting in higher soil N. At 45 DAI, the highest available N (86.6 mg kg^{-1} soil) was recorded under 75% STB NPK +

FYM + biofertiliser consortium, which was on par with 100% RDF + FYM + biofertiliser consortium (85.9 mg kg^{-1} soil), 100% RDF + FYM (85.7 mg kg^{-1} soil), and STB NPK (83.1 mg kg^{-1} soil). Further, it was observed that in treatments receiving N solely from inorganic sources, available N increased up to 30 DAI, whereas in treatments receiving FYM and the biofertiliser consortium alongside inorganic fertilisers, the increase continued up to 45 DAI. Thereafter, all treatments showed a decline in soil N content. In the control treatment, which received no inputs, available N remained more or less unchanged. The increase in available N up to 30 DAI across treatments may be attributed to N release from urea granules. The subsequent decline in treatments receiving inorganic nutrient sources might have resulted from the loss of available nitrogen through volatilisation (Burger and Venterea, 2008) and ammonia fixation in the clay lattice at 45 and 60 DAI. The increase in available N up to 45 DAI in treatments receiving inorganic nutrients together with FYM and biofertilisers might have resulted from mineralisation of organic N and biological nitrogen fixation by free-living microorganisms. The decline in available N after 45 DAI under these treatments was slight. A similar pattern was observed at 60 DAI (Table 3).

3.2 Available Phosphorus

In red loam soil, available phosphorus content at 15 DAI was significantly higher under 100% RDF + FYM + biofertiliser consortium (7.10 mg kg^{-1} soil), which was on par with 100% RDF + FYM (6.89 mg kg^{-1} soil), STB NPK (6.61 mg kg^{-1} soil), and 75% STB NPK + FYM + biofertiliser consortium (6.52 mg kg^{-1} soil). At 30 DAI, available phosphorus content was significantly higher under 100% RDF + FYM + biofertiliser consortium (7.25 mg kg^{-1} soil), which was on par with 100% RDF + FYM (7.0 mg kg^{-1} soil), STB NPK (6.71 mg kg^{-1} soil), and 75% STB NPK + FYM + biofertiliser consortium (6.66 mg kg^{-1} soil). Up to 45 DAI, all treatments except the control showed an increasing trend in available P, and the pattern of P content was similar to that observed on the previous sampling days. However, at 60 DAI, soil P content declined, and the highest available phosphorus content was recorded under 100% RDF + FYM + biofertiliser consortium (7.56 mg kg^{-1} soil), which was on par with 100% RDF + FYM (7.19 mg kg^{-1} soil); 75% STB NPK + FYM + biofertiliser consortium recorded 7.02 mg kg^{-1} soil (Table 4).

The increase in available phosphorus content up to 45 DAI might have resulted from the release of P from the applied fertiliser (SSP), FYM, and the solubilisation of native P by PSB. SSP applied to the soil reacts with soil moisture, resulting in the release of orthophosphoric acid and dicalcium phosphate; the released orthophosphoric acid then diffuses into the surrounding soil (Basak, 2016). FYM might also contribute phosphorus through mineralisation, while in treatments receiving the biofertiliser consortium, PSB might have solubilised native insoluble P (Vanitha *et al.*, 2020). In addition, the continuous availability of moisture may promote the solubilisation of P associated with colloidal complexes, releasing phosphorus into the labile pool and making it available (Vanitha *et al.*, 2020).

Table 4. Effect of integrated nutrient management on soil available phosphorus content (mg kg^{-1}) during incubation period in red loam soils

Treatments	15 DAI	30 DAI	45 DAI	60 DAI
100% RDF	6.12	6.21	6.48	6.28
100% RDF+ FYM	6.89	7.00	7.30	7.19
100% RDF+ FYM+ BC	7.10	7.25	7.64	7.56
75 % RDF	5.42	5.41	5.68	5.52
75 % RDF + FYM	5.63	5.73	6.03	5.89
75 % RDF + FYM+ BC	5.90	6.03	6.42	6.34
STB NPK	6.61	6.71	7.01	6.89
75% STB NPK+FYM	6.42	6.51	6.84	6.76
75% STB NPK+FYM + BC	6.52	6.66	7.09	7.02
Control	5.12	5.15	5.14	5.17
Mean	6.16	6.27	6.56	6.46
Sem±	0.30	0.30	0.30	0.31
CD (p=0.05)	0.67	0.66	0.67	0.68
CV	4.87	4.75	4.61	4.72

BC= Biofertilizer consortium, RDF= Recommended dose of fertilizer, STB NPK= Soil test based NPK

Furthermore, as the amount of added P increased gradually, $H_2PO_4^-$ may have been adsorbed until the sorption sites were satisfied, while the remaining $H_2PO_4^-$ may have been transferred to the labile pool, thereby increasing P availability. Similar findings were reported by Nanthakumar and Panneerselvam (2017). Examination of the treatments showed that treatments receiving FYM + biofertiliser consortium released more P, followed by the FYM-applied treatment. The decline in available phosphorus at 60 DAI might have resulted from the conversion of available phosphorus into unavailable inorganic forms over time (Halder *et al.*, 2020). The present study used red loam soil, which contains free iron and aluminium ions and oxides that might fix phosphate as a bidentate complex through chelation on ferrol and aluminol surfaces. This bidentate complex is more tightly bound, thereby reducing the amount of phosphorus available to the labile pool (Vanitha *et al.*, 2020). The decline at 60 DAI was marginal under the FYM + BC and FYM treatments, indicating that P fixation might be reduced by FYM application because humate ions compete with phosphate ions for the same fixation sites (Guppy *et al.*, 2005).

3.3 Available Potassium

In red loam soil, available potassium content at 15 DAI was significantly higher under 100% RDF + FYM + biofertiliser consortium (88.9 mg kg^{-1} soil), which was on par with 100% RDF + FYM (88.0 mg kg^{-1} soil), 100% RDF (86.2 mg kg^{-1} soil), 75% STB NPK (85.7 mg kg^{-1} soil), 75% STB NPK + FYM + biofertiliser consortium (84.1 mg kg^{-1} soil), and 75% STB NPK + FYM (82.6 mg kg^{-1}

soil). At 30 DAI, significantly higher available potassium was recorded under 100% RDF + FYM + biofertiliser consortium (94.2 mg kg^{-1} soil), which was on par with 100% RDF + FYM (92.9 mg kg^{-1} soil), 100% RDF (90.2 mg kg^{-1} soil), STB NPK (88.9 mg kg^{-1} soil), and 75% STB NPK + FYM + biofertiliser consortium (86.8 mg kg^{-1} soil). Similarly, at 45 DAI, higher available potassium was recorded under 100% RDF + FYM + biofertiliser consortium (97.3 mg kg^{-1} soil), which was on par with 100% RDF + FYM (96.0 mg kg^{-1} soil), 100% RDF (92.9 mg kg^{-1} soil), STB NPK (92.0 mg kg^{-1} soil), and 75% STB NPK + FYM + biofertiliser consortium (89.9 mg kg^{-1} soil). At 60 DAI, higher available potassium was recorded under 100% RDF + FYM + biofertiliser consortium (100 mg kg^{-1} soil), which was on par with 100% RDF + FYM (98.7 mg kg^{-1} soil), 100% RDF (95.1 mg kg^{-1} soil), STB NPK (94.7 mg kg^{-1} soil), and 75% STB NPK + FYM + biofertiliser consortium (92.1 mg kg^{-1} soil). Further examination of the data showed that available potassium continued to increase in the soil up to 60 DAI, and the release of available potassium was greater under treatments integrating inorganic sources with FYM and biofertilisers (Table 5).

Table 5. Effect of integrated nutrient management on soil available potassium content (mg kg^{-1}) during incubation period in red loam soils

Treatment	15 DAI	30 DAI	45 DAI	60 DAI
100% RDF	86.2	90.2	92.9	95.1
100% RDF+ FYM	88.0	92.9	96.0	98.7
100% RDF+ FYM+ BC	88.9	94.2	97.3	100
75 % RDF	78.2	80.9	83.1	85.3
75 % RDF + FYM	79.5	82.6	85.3	88.0
75 % RDF + FYM+ BC	80.4	84.4	87.1	90.2
STB NPK	85.7	88.9	92.0	94.7
75% STB NPK+FYM	82.6	85.3	87.5	88.9
75% STB NPK+FYM + BC	84.1	86.8	89.9	92.1
Control	73.2	75.0	76.4	77.3
Mean	82.7	86.1	88.8	91.1
Sem±	2.45	3.40	3.56	3.87
CD (p=0.05)	5.47	7.57	7.92	8.63
CV	2.97	3.95	4.01	4.25

BC= Biofertilizer consortium, RDF= Recommended dose of fertilizer, STB NPK= Soil test based NPK

The continuous release of K from the fertiliser could account for the increase in available K in the soil, while the decomposition of FYM and the activity of potassium-solubilising microorganisms could provide additional sources. K solubilisers produce organic acids that acidify the soil environment and solubilise K from native minerals (Ahmad *et al.*, 2016). K fixation by the clay lattice is a common phenomenon in soil; however, red soils have a low K-fixation tendency because their dominant minerals are kaolinite or iron-aluminium oxides, which have zero K-fixation power (Chatterjee *et al.*, 2014).

3.4 Available Sulphur

In red loam soil, available sulphur at 15 DAI was significantly higher under STB NPK (12.1 mg kg^{-1} soil), which was on par with 100% RDF + FYM + biofertiliser consortium (11.9 mg kg^{-1} soil), 75% STB NPK + FYM + biofertiliser consortium (11.7 mg kg^{-1} soil), and 100% RDF + FYM (11.4 mg kg^{-1} soil). The higher amount of inorganic fertiliser received by the STB NPK treatment might have released more sulphur into the soil. However, at 30 DAI, the 100% RDF + FYM + biofertiliser consortium treatment recorded the highest available sulphur (12.7 mg kg^{-1} soil), followed by STB NPK (12.5 mg kg^{-1} soil), 75% STB NPK + FYM + biofertiliser consortium (12.4 mg kg^{-1} soil), 100% RDF + FYM (12.3 mg kg^{-1} soil), 75% STB + FYM (12.1 mg kg^{-1} soil), 75% RDF + FYM + biofertiliser consortium (11.7 mg kg^{-1} soil), 100% RDF (11.4 mg kg^{-1} soil), 75% RDF + FYM (11.1 mg kg^{-1} soil), 75% RDF (10.6 mg kg^{-1} soil), and the control (8.93 mg kg^{-1} soil).

Table 6. Effect of integrated nutrient management on soil available sulphur content (mg kg^{-1}) during incubation period in red loam soils

Treatment	15 DAI	30 DAI	45 DAI	60 DAI
100% RDF	10.4	11.4	11.3	10.4
100% RDF+ FYM	11.4	12.3	12.5	12.3
100% RDF+ FYM+ BC	11.9	12.7	12.6	12.4
75 % RDF	9.29	10.6	10.1	9.82
75 % RDF + FYM	9.82	11.1	11.4	10.8
75 % RDF + FYM+ BC	10.7	11.7	12.1	11.5
STB NPK	12.1	12.5	12.4	12.0
75% STB NPK+FYM	11.2	12.1	12.1	11.9
75% STB NPK+FYM + BC	11.7	12.4	12.8	12.4
Control	8.67	8.93	8.97	9.06
Mean	5.71	6.57	6.63	6.20
Sem±	0.28	0.27	0.23	0.23
CD (p=0.05)	0.63	0.60	0.52	0.51
CV	4.95	4.09	3.54	3.67

BC= Biofertilizer consortium, RDF= Recommended dose of fertilizer, STB NPK= Soil test based NPK

Under the 100% RDF + FYM + biofertiliser consortium treatment, the use of FYM and the biofertiliser consortium alongside inorganic fertilisers might have promoted the mineralisation of organic sulphur and the release of sulphur from inorganic sources, resulting in higher soil sulphur. At 45 DAI, the highest available sulphur (12.8 mg kg^{-1} soil) was recorded under 75% STB NPK + FYM + biofertiliser consortium, which was on par with 100% RDF + FYM + biofertiliser consortium (12.6 mg kg^{-1} soil), 100% RDF + FYM (12.5 mg kg^{-1} soil), and STB NPK (12.4 mg kg^{-1} soil). A similar trend was observed at 60 DAI (Table 6).

4. Conclusions

This study highlights the importance of balanced nutrient-management strategies that integrate organic and inorganic sources and demonstrates their influence on nutrient release in red loam soil. Nitrogen availability was influenced by the type of fertilisation. Treatments incorporating STB NPK, 100% RDF + FYM + biofertiliser consortium, and other combinations involving organic sources such as FYM and biofertiliser showed higher available nitrogen content at different stages, particularly up to 45 DAI. This pattern suggests that integrating organic and inorganic sources promoted nitrogen release through the mineralisation of organic nitrogen, biological nitrogen fixation, and release from inorganic sources. Phosphorus availability showed a similar pattern, with treatments involving organic sources and the biofertiliser consortium showing higher phosphorus content, likely because of mineralisation, solubilisation, and reduced fixation associated with organic components and microorganisms. Potassium availability increased continuously up to 60 DAI, particularly under treatments combining inorganic sources with FYM and biofertiliser, reflecting contributions from fertiliser release, organic decomposition, and microbial solubilisation. Sulphur availability followed a similar pattern, with organic-source and biofertiliser treatments showing higher sulphur content, likely because of mineralisation and release from inorganic and organic sources.

5. Limitations

This study was confined to a 60-day laboratory incubation using red loam soil under controlled moisture conditions. Therefore, the observed nutrient-release patterns may not fully represent field variability, plant nutrient uptake, seasonal weather effects, or longer-term nutrient transformations. The assessment was limited to available N, P, K, and S under the tested nutrient combinations. Consequently, extrapolation beyond these soil and incubation conditions should be made cautiously. Field-based, multi-season evaluations across contrasting red loam sites would help determine the persistence and agronomic relevance of the observed nutrient dynamics.

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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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