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Temporal Dynamics of Soil Nitrogen Pools and Nutrient Flux in Maize as Affected by Leguminous Biomass Decomposition

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ABSTRACT

A field experiment was conducted during the *rabi* (winter) season (November, 2022 to March, 2023) at the College Farm, Professor Jayashankar Telangana Agricultural University (PJTAU), Hyderabad, Telangana, India to study the effect of *in situ* green manuring on soil nitrogen dynamics in intensive maize systems. The experiment was laid out in a randomized block design with eight treatments. Maize (var. DHM 117) was sown in paired rows, while sunhemp was simultaneously established in between and incorporated *in situ* at 45 days after sowing (DAS). Nitrogen was applied at the tasselling stage in graded levels from 0 to 60 kg N ha^{-1} in green manured plots (T_1 -T_7) and compared with a farmer's practice of recommended fertilizer dose (RDF) of 240 kg N ha^{-1} without green manuring (T_8). Soil samples collected at major crop stages were analysed for ammonical nitrogen, nitrate nitrogen, total nitrogen, total carbon, and carbon-to-nitrogen (C:N) ratio. Green manuring significantly enhanced soil nitrogen fractions compared to sole maize. At tasselling, ammonical nitrogen (54.3-55.5 mg kg^{-1}) and nitrate nitrogen (44.4 - 45.4 mg kg^{-1}) were higher under green manuring than in the control (52.5 and 41.8 mg kg^{-1}, respectively). Total soil nitrogen also improved (0.0382 - 0.0420%) compared to 0.0360% in the control. Among treatments, GM+30 kg N ha^{-1} and GM + 60 kg N ha^{-1} consistently exhibited superior nitrogen status and C: N balance, indicating that *in situ* sunhemp incorporation with optimal N supplementation sustains soil quality and nutrient availability in *rabi* maize systems.

KEYWORDS: Decomposition, inorganic nitrogen fractions, maize, sunhemp, total carbon

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1. INTRODUCTION

Maize (*Zea mays* L.) is a cereal of global economic importance, widely cultivated due to its adaptability to various climates, including tropical, subtropical, and temperate regions (Pal et al., 2015). This versatility makes maize a key player in global food security (Grote et al., 2021; Poole et al., 2021), often referred to as the "queen of cereals" for its high yield potential and diverse applications (Kennett et al., 2020). Every part of the maize plant is utilized, making it an economically efficient crop (Das et al., 2008; Sharma et al., 2011). In India, maize occupies a significant area of cultivated land, totalling approximately 10.04 mha, with a production of 33.62 million metric tonnes (mmt) and an average productivity of 3,349 kg ha^{-1}. It contributes about 8% to the national food basket (Anonymous, 2022a). In the state of Telangana, maize is the fourth most prominent crop. Recent years have seen a shift in cropping trends in Telangana, particularly following the state government's strategy for crop diversification aimed at reducing surplus production and stabilizing market prices. As a result, *rabi* maize has gained prominence, with 66.72% of the total maize area (228,000 ha) being sown during this season (Anonymous, 2022b). Maize is a nutrient-intensive crop with high nitrogen (N) requirements (Zhang et al., 2025). Among all primary nutrients, nitrogen is often the most limiting factor for maize productivity due to its dynamic behaviour in the soil-plant system (Amanullah et al., 2016). Generally, for *rabi* maize, a total of 240 kg of N ha^{-1} is recommended to fully exploit the genetic potential of modern hybrids. However, the efficiency of nitrogen utilization in maize remains suboptimal (Yu et al., 2022). According to Hofman and Cleemput (2004), a significant amount of applied nitrogen is lost due to processes such as leaching, volatilization, denitrification, immobilization, and adsorption to clay colloids (Sharma et al., 2011). These losses not only decrease the effective uptake of nitrogen by plants but also contribute to groundwater contamination and greenhouse gas emissions (Smerald et al., 2023; Sha et al., 2023; Kundu et al., 2025a). To tackle these challenges and enhance nitrogen use efficiency (NUE), it is essential to adopt sustainable and integrated nutrient management strategies (Cicek et al., 2014; Ferrara et al., 2021; Gruter et al., 2017). Organic inputs, such as green manures, crop residues, and compost, can supplement or partially replace inorganic fertilizers by adding to the soil nitrogen pool through mineralization (Datta et al., 2017). Among these options, utilizing green manures with leguminous crops like sunhemp (*Crotalaria juncea* L.) is an effective approach to improve soil fertility (Channagouda et al., 2015). Sunhemp is a fast-growing plant that fixes atmospheric nitrogen through a symbiotic relationship with rhizobia and produces substantial biomass within a short period (Kumar et al., 2023). When incorporated into the soil, the decomposing green biomass undergoes microbial breakdown, releasing vital nutrients, particularly nitrogen (McCauley et al., 2012). This process affects several important nitrogen forms in the soil, including ammonical nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), and total nitrogen, while also influencing the carbon-to-nitrogen (C:N) ratio, which regulates the timing and rate of nutrient release. A lower C: N ratio typically suggests faster decomposition and nitrogen mineralization, while a higher ratio may temporarily immobilize nitrogen. Incorporating green manure is known to boost total soil nitrogen and microbial biomass, thereby supporting long-term nutrient availability (Kundu et al., 2025b). Therefore, this investigation aims to study the effects of incorporating intercropped sunhemp at 45 days after sowing, along with different nitrogen levels applied at the tasselling stage, on soil ammonical nitrogen, nitrate nitrogen, total nitrogen, total carbon, and the C: N ratio.

2. MATERIALS AND METHODS

2.1. Experimental site and climatic conditions

The present investigation was conducted at the College Farm, College of Agriculture, Professor Jayashankar Telangana Agricultural University, Rajendranagar, Hyderabad. The farm is situated at an elevation of 542.5 meters above mean sea level, at a latitude of 17°32'18" N and a longitude of 78°41'31" E. This experimental area falls within the Southern Telangana Agro-Climatic Zone. During the field trial, the maximum temperatures ranged from 28.0 to 34.0°C, while the minimum temperatures varied between 10 and 18°C. The total rainfall recorded was 8.2 mm. Relative humidity levels fluctuated between 75 to 92% for the highest levels, and 19 to 59% for the lowest. The average daily sunshine duration was between 4.4 and 10.1 hours. Wind speeds ranged from 2.0 to 4.1 km h^{-1}, and the evaporation rate during the crop growth phase varied from 2.4 to 5.4 mm day^{-1}.

2.2. Experimental design and treatment details

The field experiment was carried out using a randomized block design (RBD), with three replications and eight treatments: T_1: *in-situ* green manuring of sunhemp at 45 DAS (GM)+0 kg N ha^{-1} at tasseling (T), T_2: GM+10 kg N ha^{-1} at T, T_3: GM+20 kg N ha^{-1} at T, T_4: GM+30 kg N ha^{-1} at T, T_5: GM+40 kg N ha^{-1} at T, T_6: GM+50 kg N ha^{-1} at T, T_7: GM+60 kg N ha^{-1} at T, and T_8: Farmer's Practice (RDF without green manuring). The maize variety DHM 117 was sown in paired rows with a spacing of 30-90-30×20 cm^2. The sunhemp with a seed rate of 50 kg ha^{-1} was sown manually as green manure in two solid rows spaced at 30 cm between the maize pairs on the same day. The crop was incorporated *in situ* at 45 DAS using a handoperated power weeder (two passes), mixing the biomass into the top 10–15 cm soil layer. Unincorporated residues were manually covered with soil to ensure uniform mixing. Observations were recorded at knee-high (30 DAS), 45 DAS, pre-tasselling (60 DAS), tasselling (70 DAS), grain filling (90 DAS), and harvest (135 DAS).

2.3. Collection and analysis of soil and plant samples

Soil samples were collected randomly from a depth of 0 to 15 cm for analysis at various stages: at the time of sowing, during pre-tasseling, tasseling, grain filling, and at harvest. The soil samples were air-dried, ground, and sieved using a 2 mm mesh sieve. They were then analyzed for total nitrogen, total carbon, and inorganic nitrogen fractions. Total carbon (TC) was determined by the loss-on-ignition method as described by Tiessen and Moir (1993), while total nitrogen (TN) was estimated using the Kjeldahl digestion method (Page et al., 1982). Ammonical nitrogen (NH_4^+-N) and nitrate nitrogen (NO_3^--N) were quantified following the standard colorimetric procedures of Bremner (1965) and Cataldo et al. (1975), respectively. Additionally, maize plant samples taken from the gross plot were analyzed for their nitrogen (N), phosphorus (P), and potassium (K) content at the same stages: at the time of green manuring, pre-tasseling, tasseling, grain filling, and harvest.

2.4. Statistical analysis

The data previously mentioned were collected, and a statistical analysis was conducted using the Analysis of Variance (ANOVA) method (Gomez and Gomez, 1984). The significance of various sources of variation was assessed using the Error Mean Square through Fisher and Snedecor's F-test at a probability threshold of 0.05. To determine the essential differences at the 5% significance level, the Fisher and Yates table (Fisher and Yates, 1963) was consulted. The OPSTAT program was used to perform the statistical analysis.

3. RESULTS AND DISCUSSION

3.1. Inorganic nitrogen fractions

The temporal variation in inorganic nitrogen fractions, particularly NH_4^+-N and NO_3^--N, showed significant differences among treatments in response to *in situ* green manuring at 45 DAS and variable nitrogen application at the tasselling stage. The release patterns of them showed an increasing trend up to the tasseling stage, then a gradual decline was noticed as the crop matured. At the knee-high stage, intercropped maize with green manure (T_1-T_7) treatments consistently recorded higher amounts of NH_4^+-N (45.0-46.2 mg kg^{-1}) and NO_3^--N (36.8-37.8 mg kg^{-1}) concentrations compared to the (T_8)- sole maize treatment (43.6 and 34.7 mg $kg^{-1,}$ respectively). This trend continued through 45 DAS (At the time of green manuring), where NH_4^+-N ranged from 49.9 to 51.1 mg kg^{-1} and NO_3^--N from 40.8 to 41.8 mg kg^{-1} in green manured treatments (T_1-T_7), whereas the T_8 treatment showed lower concentrations (48.1 mg kg^{-1} NH_4^+-N and 38.6 mg kg^{-1} NO_3^--N). The higher concentrations in the green manured plots may be due to the nitrogen contribution through biological nitrogen fixation, organic matter decomposition, and the transfer of legume-derived nutrients to the maize crop. Similar results were reported by Hanly and Gregg (2004), who recorded improved mineralization and nitrogen availability in green manured treatments. During the pre-tasselling stage, NH_4^+-N and NO_3^--N concentrations increased more in all the green manured treatments, which continued to outperform the sole maize treatment (T_8). In green manured treatments (T_1–T_7), the ammonical nitrogen concentration is in the range of 51.4 and 52.6 mg kg^{-1}, while nitrate nitrogen concentration is 42.1 to 43.0 mg kg^{-1}, but the T_8 sole maize registered lower concentrations ranging from 38.9 to 49.6 mg kg^{-1}, respectively. The synchrony between nitrogen immobilization and release was mostly governed by the decomposition of green manure and active microbial assimilation, supporting the conclusions of Haynes et al. (1993), who reported that crop residues with >2% nitrogen induce mineralization when incorporated into soil. At the tasseling stage, the maximum mineralization nitrogen was observed, where NH_4^+-N concentration is in the range of 54.3 to 55.5 mg kg^{-1} and NO_3^--N is in the range of 44.4 to 45.4 mg kg^{-1} across the green manured treatments. The sole maize treatment (T_8) continued to lag (NH_4^+-N: 52.5; NO_3^--N: 41.8 mg kg^{-1}), reflecting the importance of legume-based green manuring in improving the nitrogen availability in soil (Tables 1 and 2).

A declining trend was noticed in both forms of nitrogen from the grain-filling to harvesting. The treatments T_4 (green manure+30 kg N ha^{-1} at tasseling) and T_7 (green manure+60 kg N ha^{-1} at tasselling) maintained significantly higher concentrations of NH_4^+-N (T_4: 51.8, 45.7 mg kg^{-1}; T_7: 50.8, 44.9 mg kg^{-1}) and NO_3^--N (T_4: 42.4, 37.4 mg kg^{-1}; T_7: 41.6, 36.6 mg kg^{-1}) compared to other. The treatments T_5 and T_6 (green manure + 40 and 50 kg N ha^{-1}, respectively) also recorded good concentrations, but slightly lower compared to treatment T_4, possibly due to more nitrogen losses at greater soil nitrogen availability. In contrast, the treatments T_1 and T_2 (green manure with 0 and 10 kg N ha^{-1} at tasselling) recorded lower concentrations of NH_4^+-N (grain filling: 46.2, 47.4 mg kg^{-1}; harvest: 40.1, 41.3 mg kg^{-1}) and NO_3^--N (grain filling: 37.8, 38.8 mg kg^{-1}; harvest: 32.8, 33.8 mg kg^{-1}), reflecting the limited nitrogen input and reduced microbial-mediated mineralization in these treatments. From these observations, it is evident that green manure played the most important role in both enhancing microbial activity and synchronizing nitrogen release with

Table 1: NH_4^+N of soil in response to *in situ* green manuring at 45 DAS and variable nitrogen split application at the tasseling stage

Treat-ments	Knee high	Pre-tasselling	Tasselling	Grain filling	Harvest
T_1	45.7	52.0	55.0	46.2	40.1
T_2	46.2	52.6	55.5	47.4	41.3
T_3	45.2	52.1	54.5	48.2	42.0
T_4	46.2	52.6	55.5	51.8	45.7
T_5	45.3	52.3	55.2	49.6	43.5
T_6	45.5	51.8	54.8	50.1	43.7
T_7	45.0	51.4	54.3	50.8	44.9
T_8	43.6	49.6	52.5	49.1	43.0
SEm±	0.6	0.6	0.7	0.5	0.5
CD (p=0.05)	1.7	1.9	2.1	1.5	1.6

T_1: *In situ* green manuring of sunhemp at 45 DAS (GM)+0 kg N ha^{-1} at tasselling (T) stage; T_2: GM+10 kg N ha^{-1} at T; T_3: GM+20 kg N ha^{-1} at T; T_4: GM+30 kg N ha^{-1} at T; T_5: GM+40 kg N ha^{-1} at T; T_6: GM+50 kg N ha^{-1} at T; T_7: GM+60 kg N ha^{-1} at T; T_8: Farmer's practice

Table 2: NO_3^-N of soil in response to *in situ* green manuring at 45 DAS and variable nitrogen split application at the tasseling stage

Treat-ments	Knee high	Pre-tasselling	Tasselling	Grain filling	Harvest
T_1	37.4	42.6	45.0	37.8	32.8
T_2	37.8	43.0	45.4	38.8	33.8
T_3	37.0	42.6	44.6	39.4	34.4
T_4	37.8	43.0	45.4	42.4	37.4
T_5	37.0	42.8	45.2	40.3	35.3
T_6	37.2	42.4	44.8	40.5	35.5
T_7	36.8	42.1	44.4	41.6	36.6
T_8	34.7	38.9	41.8	40.2	35.2
SEm±	0.7	1.2	1.0	0.5	0.5
CD (p=0.05)	2.1	3.7	3.1	1.5	1.6

crop demand. Among the inorganic nitrogen fractions, the NH_4^+-N is more readily available and requires less energy for maize uptake, showing an initial dominance, whereas the NO_3^--N concentrations closely followed, affirming the gradual nitrification process after the post-ammonification. Nitrogen availability and uptake are collectively improved by these dynamics across key growth stages of maize. These observations support the earlier findings of Hofman and Cleemput (2004) and highlight that optimal integration of organic and inorganic N sources for improving the nitrogen efficiency and sustainability in maize-based cropping systems.

3.2. *Total carbon and total nitrogen*

The total carbon and total nitrogen in the soil displayed distinct trends over time and across various treatments at different growth stages of the maize crop, particularly in response to green manuring and varying nitrogen application at the tasselling stage. While total carbon values did not show significant differences among treatments at any stage, a slight upward trend was observed following the incorporation of green manure, especially up to the pre-tasselling stage. This suggests a short-term impact of organic inputs. In contrast, total nitrogen exhibited a more dynamic pattern, with significant variations arising from both green manures intercropping and the rate of nitrogen applied at tasselling. At the knee-high stage, all treatments had comparable total carbon values ranging from 0.50 to 0.55%. This trend continued up to 45 DAS, the point of green manure incorporation, where total carbon values ranged between 0.48 and 0.56% across treatments (Figure 1).

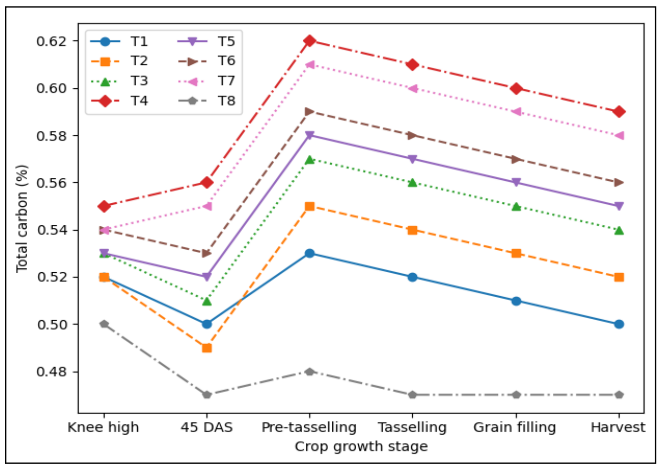

Figure 1: Temporal dynamics of total carbon (%) in soil

The incorporation of approximately 8.2 to 9.0 t ha^{-1} of fresh biomass through green manuring, although considerable, did not significantly alter soil carbon levels due to the rapid decomposition of leguminous biomass and associated microbial respiration, which releases carbon as carbon dioxide (CO_2). Additionally, both aboveground contributions (such as leaf fall and leaching) and belowground contributions (including roots, sloughed cells, and border cells) from the green manure crops enriched the labile carbon pool. However, these did not result in statistically significant differences in total carbon, likely due to a balance between inputs and losses (Yusuf et al., 2009; Thilakarathna et al., 2016). By the pre-tasselling and tasselling stages, a slight decline in total carbon was recorded, with values ranging from 0.47 to 0.62% and 0.47 to 0.61%, respectively, followed by further reductions toward harvest, where values ranged from 0.47 to 0.59%. Total nitrogen content showed significant variations across different treatments and growth stages. At the knee-high stage, treatments involving maize intercropped with green manure (T_1-T_7) consistently exhibited higher total nitrogen contents, ranging from 0.0437 to 0.0454%, compared to T_8 (sole maize), which recorded 0.0431%. At 45 DAS, coinciding with the incorporation of green manure, a clearer differentiation was observed. Treatments T_1-T_7, which included leguminous intercropping, showed higher total nitrogen values ranging from 0.043 to 0.047%, while the T_8 treatment maintained the lowest value at 0.043% (Figure 2).

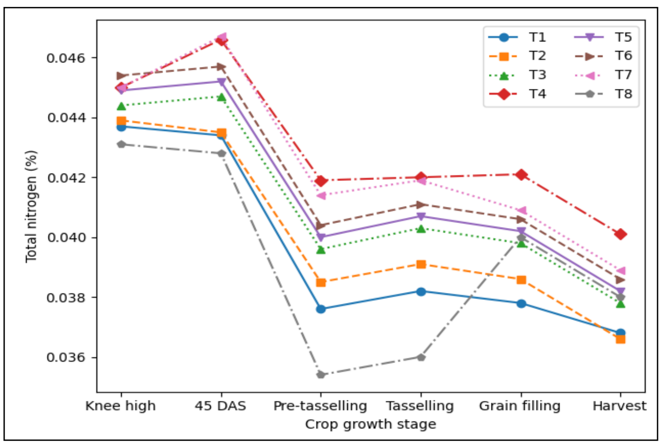

Figure 2: Temporal dynamics of total nitrogen (%) in soil

This increase in total nitrogen in green manured plots can be attributed to the biological nitrogen fixation capability of the legume (sunhemp) and the transfer of nitrogen from legumes to the maize crop. Nutrient transfer in these systems occurs through both aboveground pathways (leaf exudation, litterfall) and belowground pathways (root exudates, decomposed root tissues, nodules, and sloughed epidermal cells), enriching the nitrogen pool available to the companion crop (Yusuf et al., 2009; Thilakarathna et al., 2016). During the pre-tasselling stage,

Total nitrogen levels declined slightly across all treatments, which is typical due to plant uptake and microbial immobilization. However, the green manured treatments (T_1–T_7) maintained a higher nitrogen status (0.0376 to 0.0419%) compared to the non-green manured sole maize treatment T_8 (0.0354%). In the subsequent tasselling stage, following the application of split nitrogen doses, a minor rebound in soil total nitrogen was observed, particularly in T_4 and T_7, which received 30 and 60 kg N ha^{-1}, respectively, at tasselling, in addition to prior green manuring. As the crop progressed to the grain filling and harvest stages, the effects of differential nitrogen application became more pronounced. T_4, with 30 kg N ha^{-1} applied at tasselling, consistently recorded the highest total nitrogen levels at grain filling (0.0421%) and harvest (0.0401%). The treatment, T_7, despite receiving 60 kg N ha^{-1}, exhibited slightly lower values (grain filling: 0.0409%; harvest: 0.0389%), likely due to greater nitrogen losses under surplus conditions. Treatments T_5 and T_6 (40 kg and 50 kg N ha^{-1}, respectively) displayed comparable trends but did not exceed T_4, indicating that moderate nitrogen application combined with green manuring optimizes soil nitrogen retention. Intermediate soil nitrogen levels were noted in T_3 and T_8, while the lowest values at both grain filling and harvest occurred with T_1 and T_2 (0 kg and 10 kg N ha^{-1} at tasselling), emphasizing the inadequacy of green manure alone to sustain total nitrogen levels at later growth stages.

In summary, the combination of green manuring with strategic nitrogen application positively impacted total nitrogen dynamics, while total carbon levels remained relatively stable due to rapid turnover and balanced carbon input-output dynamics. The integration of green manure with moderate nitrogen supplementation, especially evident in T_4, proved effective in enhancing soil nitrogen status without significant nitrogen losses, highlighting the ecological and agronomic value of such integrated nutrient management strategies in intensive maize-based systems.

3.3. Carbon to nitrogen (C:N) ratio

The carbon-to-nitrogen (C: N) ratio is a crucial indicator of soil organic matter balance, microbial activity, and nutrient cycling. In this study, significant variations were observed among different treatments throughout the crop growth period, showing an increasing trend up to the pre-tasseling stage, followed by a decline towards harvest. At the knee-high stage, treatments T_1-T_7 (maize + green manure) recorded higher and comparable soil C: N ratios (11.8-12.2), while treatment T_8 (sole maize) had a lower ratio of 11.6. This difference reflects early organic inputs from the roots, nodules, and sloughed cells of the green manure (Thilakarathna et al., 2016; Yusuf et al., 2009). At 45 DAS, coinciding with the incorporation of green manure, the soil C: N ratio in treatments T_1-T_7 ranged from 11.4 to 12.0, whereas T_8 maintained a lower ratio of 11.0. The slightly higher ratios in the green-manure plots indicate enhanced organic inputs, consistent with findings of Yusuf et al. (2009), which reported nutrient transfer through both above-ground and below-ground biomass in cereal-legume intercropping. By the pre-tasseling stage, C: N ratios increased further (T_1–T_7: 14.1-14.9; T_8: 13.3) due to the decomposition of green manure biomass (8.2-9.0 t ha^{-1}) (Figure 3)

According to Anonymous (2022c), a soil C: N ratio of

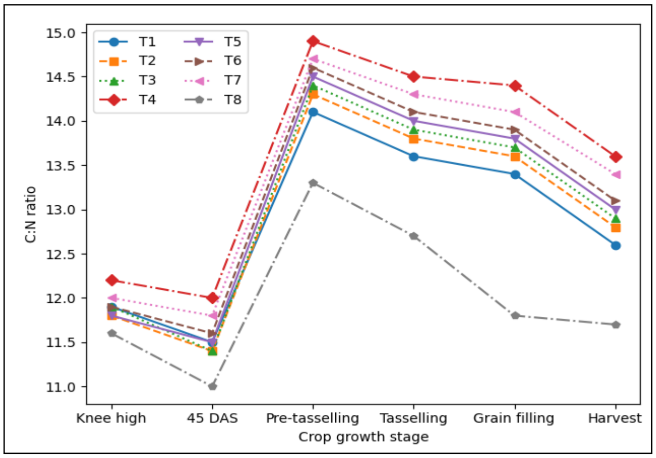

Figure 3: Temporal dynamics of the C:N ratio of soil

approximately 10:1 reflects a dynamic equilibrium; thus, the higher ratios observed in this study indicate carbon enrichment from organic additions. At the tasseling stage, C: N ratios declined (T_1–T_7: 13.6-14.5; T_8: 12.7), indicating the onset of carbon decomposition and nitrogen mineralization. The reduction in microbial biomass at this stage reinforced the transition from immobilization to mineralization. During the grain-filling stage, C: N ratios ranged from 11.8 to 14.4. Treatment T_4 (14.4) and T_7 (14.1), which received 30 and 60 kg N ha^{-1}, respectively, at tasseling, maintained higher ratios. Treatments T_3, T_5, and T_6 (13.7-13.9) were comparable to T_7. The nitrogen additions at tasseling likely supported microbial populations and slowed carbon decomposition, facilitating a synchronized release of nutrients. At harvest, this trend continued with T_4 (13.6) and T_7 (13.4) showing the highest C: N ratios, followed by T_5 (13.0) and T_6 (13.1). The lowest ratio was again recorded in T_8 (11.7), indicating a faster carbon turnover due to limited organic input. These findings confirm that leguminous green manures, which have inherently low C: N ratios (<25:1), decompose efficiently without causing nitrogen immobilization. Their inclusion improved soil organic carbon levels and supported nutrient cycling throughout the crop season, in line with Anonymous (2022c) guidelines for sustainable soil health.

3.4. Plant nutrient uptake

The uptake of major macronutrients nitrogen (N), phosphorus (P), and potassium (K) by maize plants showed a consistent and linear increase from the early vegetative stage to harvest. This increase was influenced by the use of green manuring and varying nitrogen application at the tasselling stage. The growing height of the plants and the expanding root system over time contributed to more effective nutrient acquisition, as indicated by improved nutrient uptake during all observation stages. The data from the various treatments suggest that the combined effect of incorporating green manure *in situ* at 45 DAS and supplementary nitrogen application at the tasselling stage was crucial for enhancing nutrient uptake. At the knee-high stage, maize grown in T_1–T_7 treatments demonstrated superior nutrient uptake: nitrogen ranged from 11.7 to 12.9 kg ha^{-1}, phosphorus from 2.40 to 2.70 kg ha^{-1}, and potassium from 11.5 to 12.7 kg ha^{-1}. In contrast, the sole maize treatment (T_8) had lower nutrient uptakes, with nitrogen at 11.0 kg ha^{-1}, phosphorus at 2.10 kg ha^{-1}, and potassium at 10.9 kg ha^{-1}. The nutrient advantage seen in treatments T_1–T_7 is attributed to enhanced nutrient mobilization and biological nitrogen fixation due to the presence of legume green manure crops. Following the incorporation of green manure biomass (approximately 8.2 to 9.0 t ha^{-1}) at 45 DAS, an external source of nutrients, particularly N, P, and K, resulted in a slight increase in nutrient uptake before the tasselling stage. Improved root-soil interaction and the microbial decomposition of green manure likely increased nutrient availability, which was evident during the pre-tasselling stage. At this point, the uptake of nitrogen, phosphorus, and potassium in green manured treatments (T_1–T_7) ranged from 83.9 to 90.1, 15.3 to 16.5 and 82.2 to 86.5 kg ha^{-1}, respectively, while T_8 recorded lower values: nitrogen at 81.5 kg ha^{-1}, phosphorus at 14.8 kg ha^{-1}, and potassium at 80.3 kg ha^{-1}. At the tasselling stage, nutrient uptake peaked in the green manured treatments: nitrogen ranged from 114 to 119 kg ha^{-1}, phosphorus from 19.4 to 22.1 kg ha^{-1}, and potassium from 112 to 115 kg ha^{-1}. In comparison, T_8 lagged with nitrogen, phosphorus, and potassium uptakes of 111 kg ha^{-1}, 18.1 kg ha^{-1}, and 108 kg ha^{-1}, respectively. The grain-filling stage represented a time of high nutrient demand. Among all treatments, T_4 and T_7 had the highest nitrogen uptake (138 and 135 kg ha^{-1}), phosphorus (27.1 and 26.8 kg ha^{-1}), and potassium (160 and 157 kg ha^{-1}), respectively. These treatments benefited from both green manuring and supplementary nitrogen applications of 30 and 60 kg ha^{-1} during the tasselling phase. The treatments T_5 and T_6, which received 40 and 50 kg N ha^{-1}, also exhibited competitive uptakes, particularly for phosphorus and potassium. Conversely, T_1–T_3 (0–20 kg N ha^{-1} at tasselling) and T_8 (recommended N without green manuring) showed relatively lower nutrient uptakes at this stage. At harvest, nutrient partitioning indicated that nitrogen and phosphorus were more concentrated in the grain, while potassium primarily accumulated in the stover (Tables 3, 4, and 5).

Nitrogen uptake by maize stover ranged from 63.0 to 82.0 kg ha^{-1}, with T_4 and T_7 recording the highest values. Grain nitrogen uptake reflected this distribution, with T_4 and T_7 again showing the highest values at 118.0 kg ha^{-1}. Phosphorus uptake by stover ranged from 12.2 to 14.0 kg ha^{-1}, and by grain from 19.0 to 21.8 kg ha^{-1}, with T_4 and T_7 continuing to perform well. Furthermore, potassium

Table 3: Nitrogen uptake by maize in response to *in situ* green manuring at 45 DAS and variable nitrogen split application at the tasseling stage

Treatments	Knee high	Pre-tasselling	Tasselling	Grain filling	Harvest (Stover)	Harvest (Grain)
T_1	12.0	83.9	114.0	118.0	63.0	91.0
T_2	11.7	85.7	115.0	120.0	71.8	100.3
T_3	12.2	86.2	114.0	123.0	74.0	101.4
T_4	12.9	90.1	119.0	138.0	82.0	118.4
T_5	11.9	86.8	115.0	126.0	72.1	109.1
T_6	12.6	87.3	116.0	129.0	71.4	113.7
T_7	12.8	89.4	117.0	134.0	76.4	117.7
T_8	11.0	81.5	111.0	125.0	71.2	107.4
SEm±	0.5	2.3	2.0	1.9	1.9	1.2
CD (p=0.05)	1.4	6.8	6.2	5.7	5.7	3.5

Table 4: Phosphorus uptake by maize in response to *in situ* green manuring at 45 DAS and variable nitrogen split application at the tasseling stage

Treatments	Knee high	Pre-tasselling	Tasselling	Grain filling	Harvest (Stover)	Harvest (Grain)
T_1	2.40	15.3	19.4	23.6	12.2	19.0
T_2	2.40	15.4	19.7	23.8	12.3	19.2
T_3	2.40	15.6	20.3	24.1	12.4	19.3
T_4	2.70	16.5	22.1	27.1	14.0	21.8
T_5	2.50	15.9	20.9	24.7	12.5	19.5
T_6	2.60	16.1	21.5	25.2	12.6	19.6
T_7	2.60	16.3	21.8	26.8	13.5	21.1
T_8	2.10	14.8	18.1	24.3	12.4	19.4
SEm±	0.10	0.4	1.1	0.4	0.3	0.5
CD (p=0.05)	0.40	1.2	3.3	1.1	1.0	1.6

Table 5: Potassium uptake by maize in response to *in situ* green manuring at 45 DAS and variable nitrogen split application at the tasseling stage

Treatments	Knee high	Pre-tasselling	Tasselling	Grain filling	Harvest (Stover)	Harvest (Grain)
T_1	11.5	82.2	112.0	148.0	162.0	25.7
T_2	11.8	83.6	112.0	149.0	163.0	25.9
T_3	12.0	84.8	113.0	149.0	163.0	26.1
T_4	12.7	86.5	115.0	160.0	174.0	29.6
T_5	12.1	84.7	113.0	151.0	165.0	26.8
T_6	12.3	85.3	114.0	152.0	165.0	27.1
T_7	12.5	86.1	115.0	157.0	171.0	28.3
T_8	10.9	80.3	108.0	149.0	163.0	26.5
SEm±	0.4	1.8	1.8	2.4	2.2	0.6
CD (p=0.05)	1.3	5.5	5.6	7.2	6.7	2.0

uptake in stover significantly exceeded grain uptake, with stover values ranging from 162 to 174 kg ha^{-1} compared to grain values of 25.7 to 29.6 kg ha^{-1}. Once again, T_4 and T_7 emerged as the most efficient treatments. The dynamics of N, P and K uptake reflect not only the influence of nitrogen application at the tasselling stage but also the synergistic role of green manure in enhancing nutrient availability and minimizing nutrient losses. Phosphorus, as the second most limiting nutrient after nitrogen, is vital for energy transfer and membrane synthesis (Daniel et al., 1998). A balanced uptake of nitrogen alongside phosphorus ensures optimal plant metabolism (Gusewell, 2004; Hu and Chu, 2020; Kant et al., 2011). Studies have shown that phosphate deficiency can impede nitrogen uptake (Lee, 1982; Rufty et al., 1990; Wang et al., 2020), reinforcing the importance of maintaining balanced N: P nutrition (Ueda et al., 2020). In this study, the balanced uptake of nitrogen and phosphorus in treatments T_4 and T_7 substantiates the necessity of synchronizing nutrient availability. Potassium uptake, crucial for enzymatic functions, water regulation, and sugar transport, exhibited rapid accumulation from tasselling to grain filling. Its preferential accumulation in stover emphasizes its essential role in maintaining plant physiology rather than solely contributing to grain filling. Thus, this study illustrates that green manuring, particularly when integrated with optimal nitrogen supplementation at the tasselling stage (30-60 kg ha^{-1}), significantly enhances the availability and uptake of N, P, and K in maize, ultimately leading to improved crop nutrition and productivity.

3.5. Grain yield of maize

The grain yield of maize was significantly influenced by green manuring and variable nitrogen split application at the tasselling stage (Figure 4). It indicated that green manuring, in addition to variable nitrogen application at the tasselling stage, has varied the grain yield from 5110 to 6687 kg ha^{-1}. In these treatments, green manuring was done along with the application of nitrogen at 30 and 60 kg ha^{-1}, respectively, during the tasselling stage. This result gives a clear indication that when green manuring

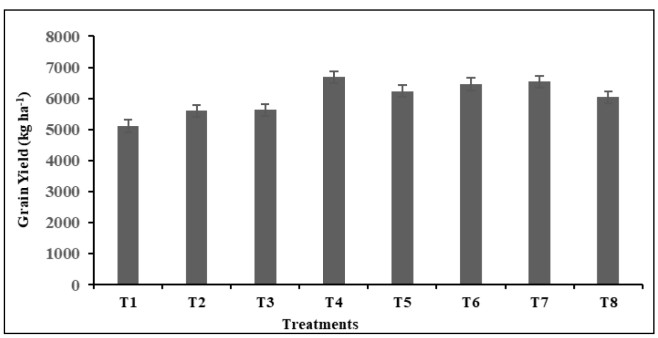

Figure 4: Grain yield (kg ha^{-1}) of maize in response to *in situ* green manuring

was administered in maize, nitrogen application up to 30 kg ha^{-1} could be compensated at the tasselling stage, thus incurring less cost with more returns. Nitrogen application at a higher rate of >30 kg ha^{-1} did not reach the level of parity except with T_7 applied with 60 kg N ha^{-1}. A higher rate of N application in this treatment might have compensated for the nitrogen losses that may have occurred. T_6 with nitrogen applied @ 50 kg ha^{-1} has reached the level of parity (6461 kg ha^{-1}) with T_7 alone, but never equalled T_4, clearly indicating the possibility of N wastage in a green manure intercropped system and compensation from the incorporated green manure. Of all the treatments, T_1 alone, in which maize was incorporated with green manure *in situ* and skipped with N-application at the tasselling stage, reported the lowest grain yield of 5110 kg ha^{-1}. Kumar et al. (2023) reported that *in-situ* green manuring with 30 kg N ha^{-1} at tasselling met crop N demand, with no yield advantage from higher rates. Moreover, Asghar and Kataoka (2022) highlighted that fast mineralization of legume residues under excessive fertilization can accelerate N losses, supporting the inefficiency of higher rates. Collectively, these findings substantiate that modest N supplementation with green manuring sustains optimum yields while minimizing wastage and nutrient loss.

4. CONCLUSION

In situ green manuring with sun hemp intercropped in maize improved soil nitrogen dynamics and overall soil quality under intensive *rabi* cultivation. Early incorporation of sun hemp enhanced soil nitrogen fractions and maintained a balanced carbon-nitrogen relationship compared to sole maize. Integration of green manuring with judicious nitrogen supplementation proved more effective than fertilizer application alone, highlighting its potential as a sustainable strategy for improving soil fertility, nutrient cycling, and long-term soil health in maize-based systems.

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