



RESEARCH ARTICLE

# Sustainable maize intensification through green manure intercrops and nitrogen management

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## Abstract

A field experiment was conducted during the Kharif and Rabi seasons of 2023-24 and 2024-25 at ZAHRS, Shivamogga, to evaluate the effect of green manure (GM) intercropping (I) and nitrogen (N) levels on growth and yield of maize in a maize-maize sequence. The experiment was laid out in a split-plot design with three N levels (75 %, 100 % and 125 % RDN) and four intercrops (sole maize, cowpea, horse gram and sun hemp). Green manures were raised in an additive series and incorporated at 45 DAS. Pooled results showed that increasing nitrogen beyond the recommended dose provided only marginal yield benefits, while GM intercropping significantly enhanced maize productivity. Among the systems tested, maize + sun hemp consistently produced the highest grain and straw yields across nitrogen levels, followed by maize + cowpea. The combination of higher nitrogen with sun hemp recorded the maximum productivity, whereas sole maize under the lowest nitrogen level recorded the lowest. The study demonstrates the strong potential of sun hemp-based intercropping to improve maize yields and contribute to the sustainable intensification of maize-based cropping systems.

**Keywords:** green manure; legume intercrops; maize; nitrogen management; sustainable intensification

**Abbreviations:** ANOVA-Analysis of variance, BD-Bulk Density, CGR-Crop Growth Rate, DAS-Days After Sowing, FYM-Farmyard Manure, GM-Green Manure, LAI-Leaf Area Index, MSL-Mean Sea Level, OC-Organic Carbon, OM-Organic Matter, RDN-Recommended Dose of Nitrogen, SPAD-Soil Plant Analysis Development (Relative chlorophyll content value), TDM-Total Dry Matter, ZAHRS-Zonal Agricultural and Horticultural Research Station, ICAR-CCARI-Indian Council of Agricultural Research-Central Coastal Agricultural Research Institute

## Introduction

Maize (*Zea mays* L.) is the third most important cereal crop in the world and a highly versatile crop used for food, feed, fodder and diverse industrial products, with growing relevance as a biofuel source (1). Native to South Mexico, it is recognized for its wide adaptability across agro-climatic conditions. It is often referred to as the Queen of Cereals owing to its diverse uses and economic significance. Globally, it occupies 206.3 m ha, producing 1219.30 m t with a productivity of 5.75 t ha<sup>-1</sup> (2). In India, maize is cultivated over 9.89 m ha with a production of 31.64 m t and an average productivity of 3.19 t ha<sup>-1</sup>. Karnataka ranks first in both area (1.72 m ha) and production (5.36 m t), with a productivity of 3.11 t ha<sup>-1</sup> (3).

Previous studies have shown that continuous cultivation of maize under intensive cropping systems often results in declining soil fertility, nutrient mining and reduced productivity. In Shivamogga, maize occupies 0.585 lakh ha, about 6.25 per cent of Karnataka's total maize area (9.36 lakh ha), replacing traditional crops like ragi, sorghum and groundnut during Kharif and short-

duration pulses and oilseed crops during Rabi season is now prevalent in taluks like Shikaripura, Shivamogga and Soraba (4). A good yield on a sustainable basis can be achieved if soil quality and health are maintained with an adequate supply of macro- and micronutrients.

Nitrogen is the most limiting nutrient for maize production, influencing growth, yield and grain quality (5). However, inefficient use and excessive application can lead to nutrient losses, environmental pollution and higher production costs (6). Enhancing nitrogen-use efficiency while sustaining yields is, therefore, a major challenge in maize-based systems.

Green manuring, particularly with leguminous crops, is a sustainable practice to enhance soil fertility and crop productivity (7,8). Legumes can fix atmospheric nitrogen, enrich soil organic matter, improve structure and stimulate microbial activity (9), providing a slow and prolonged nutrient release to subsequent crops. GM crops, when incorporated into cropping systems, can partially substitute chemical fertilizers, improve soil carbon

sequestration and sustain yields (10). Under rainfed double-cropping systems, the exclusive cultivation of GM crops is often economically unviable. Intercropping green manures with maize provides a practical alternative, allowing their simultaneous growth and subsequent incorporation without reducing the main crop area. In an additive series intercropping system, green manures can be incorporated at flowering, ensuring the release of nutrients during the critical growth stages of maize. This approach has the potential to partially substitute chemical nitrogen inputs, enhance nutrient availability and improve crop performance.

However, in Karnataka-particularly in the Southern Transition Zone-the potential of green-manure intercropping remains underexplored, despite increasing reliance on maize-based monocropping and declining soil fertility. Minimal studies have examined how leguminous GM intercrops interact with different nitrogen levels to influence maize yield stability and long-term productivity. Therefore, the present study was undertaken to assess the impact of leguminous GM intercrops with varied nitrogen levels on the growth, yield and productivity sustainability of maize under a maize-maize cropping sequence in the Southern Transition Zone of Karnataka.

## Materials and Methods

### Experimental site characteristics

The field experiment was carried out during the Kharif and Rabi seasons of 2023-24 and 2024-25 at the Zonal Agricultural and Horticultural Research Station (ZAHRS), Shivamogga (13°58'-14° 01' N, 75°34'-75°42' E; 615 m Mean Sea Level MSL). The site represents the Southern Transition Zone (Zone VII) of Karnataka. It is characterized by sandy loam, acidic Alfisols (pH 5.89), low organic carbon (4.63 g kg<sup>-1</sup>) and available N (226.72 kg ha<sup>-1</sup>), but high available P (61.08 kg ha<sup>-1</sup>) and medium K (201.23 kg ha<sup>-1</sup>).

The region receives a normal annual rainfall of 1,813 mm, predominantly from July to September. During the experimental period, total rainfall amounted to 1,756 mm (Kharif 2023), 38 mm (Rabi 2023-24), 1,842 mm (Kharif 2024) and 42 mm (Rabi 2024-25). Mean maximum and minimum temperatures ranged between 28-33 °C and 18-23 °C, respectively. Relative humidity varied from 71-89 % in Kharif and 56-74 % in Rabi (Supplementary table 1 and 2). Overall, the weather conditions supported normal crop growth, with rainfall sufficient during Kharif and irrigation provided as needed during Rabi.

### Experimental design

The study was laid out in a split-plot design with three replications, in which nitrogen levels (75 %, 100 % and 125 % of the recommended dose of nitrogen-RDN) were assigned to main plots and GM intercropping systems to subplots. The selected N levels represented sub-optimal, recommended and supra-optimal nutrient regimes to quantify maize responsiveness and assess the modifying effect of leguminous green manures under varied N supply.

The intercrops-sun hemp (MKS-03-04), fodder cowpea (MFC-09-01) and horse gram (PHG-9)-were chosen based on their rapid biomass accumulation, proven N-fixing potential, adaptability to low-input systems and suitability for short-duration in situ green manuring. A sole maize treatment was included for comparison.

The experimental area was divided into three blocks, each further subdivided into three main plots and four sub-plots,

resulting in a total of 36-unit plots (3 main plots × 4 sub-plots × 3 replications). 1 m wide drains separated the blocks, while 50 cm bunds demarcated individual unit plots within each block. The gross plot size was 7.2 m × 6.0 m with a net plot size of 6.4 m × 5.6 m. Treatments were randomly allotted to the plots within each block.

### Treatment details

#### Main plot: Nitrogen levels (N)

N<sub>1</sub>: 75 % RDN

N<sub>2</sub>: 100 % RDN

N<sub>3</sub>: 125 % RDN

#### Subplot: Intercropping systems

I<sub>0</sub>: Sole maize

I<sub>1</sub>: Maize + Cowpea

I<sub>2</sub>: Maize + Horse gram

I<sub>3</sub>: Maize + Sun hemp

Note: No fertilizer was applied to GM intercrops

FYM, P and K are common for all treatments

POP: FYM (10 t ha<sup>-1</sup>) + 150:75:40:10 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O:ZnSO<sub>4</sub> ha<sup>-1</sup>

RDN: Recommended dose of nitrogen of maize; FYM - Farm yard manure

### Crop establishment and management

Maize hybrid CP-201 was planted at 90 × 20 cm spacing under both sole and intercropped systems. Intercrops were sown between maize rows in an additive series and incorporated in situ at 45 DAS without fertilizer application. All GM seeds were treated with appropriate Rhizobium cultures to ensure effective nodulation.

A uniform dose of 7.5 t ha<sup>-1</sup> FYM was applied each season. The fertilizer schedule for the 100 % RDN treatment (150:75:40:10 kg N:P<sub>2</sub>O<sub>5</sub>: K<sub>2</sub>O:ZnSO<sub>4</sub> ha<sup>-1</sup>) was adopted proportionately for the other nitrogen levels as it was widely reported to optimize yield without excessive input. Half of the nitrogen and the full dose of P, K and Zn were applied at sowing, while the remaining nitrogen was top-dressed in two equal splits at the knee-high and tasselling stages. All recommended agronomic practices were followed to ensure optimum crop growth.

Representative field views at 60 DAS and intercrop growth before incorporation (45 DAS) are shown in Fig. 1 and Fig. 2.

### Data collection

Observations on maize growth, yield attributes and yield were recorded using standard procedures at appropriate growth stages.

The data were recorded for growth observations, *i.e.*, plant height, number of leaves, leaf area, leaf area index (LAI), dry matter production and crop growth rate (CGR). Yield parameters *viz.*, cob length, cob girth, cob weight and grains per cob and grain and straw yield was also recorded using standard procedures at appropriate growth stages.

### Statistical analysis

The data were statistically analysed through ANOVA using Microsoft Excel and OPSTAT (Operational statistics). Crop data were subjected to the least significant difference at a probability level ≤ 0.05 (11). As seasonal effects were largely non-significant for most variables, data were subsequently pooled across four seasons for final interpretation.



**Fig. 1.** Overview of the experimental plot at 45 DAS.



**Fig. 2.** General view of the experimental plot at 60 DAS.

## Results and Discussion

### Growth parameters

Dry matter accumulation drives yield, as vegetative parts act as sources and grains as sinks. Growth is regulated by morphological, physiological and biochemical processes driven by nutrient supply, light, temperature and moisture availability (12). Restricted vegetative development reduces photosynthate supply and limits reproductive growth.

Growth parameters of maize were significantly influenced by nitrogen levels, GM intercropping systems and their interaction (Table 1). Plant height, leaf production, leaf area, Leaf Area Index (LAI), total dry matter and Crop Growth Index (CGR) at 90 DAS all increased with higher nitrogen application, showing a clear positive response to improved N availability. Growth gains were substantial from 75 % to 100 % Recommended dose of nitrogen of maize (RDN) and tended to plateau beyond this level, as 125 % RDN remained statistically on par with 100 % RDN for most traits. These responses highlight the central role of nitrogen in

stimulating meristematic activity, cell division, leaf expansion and chlorophyll formation, thereby enhancing photosynthetic efficiency and biomass accumulation. Similar positive responses of maize growth to higher nitrogen supply were reported (13-16).

Among intercropping treatments, maize + sun hemp ( $I_3$ ) recorded consistently highest plant height, leaf number, leaf area, LAI, total dry matter and CGR, followed by maize + cowpea, with the lowest values in sole maize. The superior performance with sun hemp is largely due to its greater biological N-fixation capacity, rapid growth and higher biomass production, which contribute more organic matter upon incorporation. GM intercropping, especially with sun hemp and cowpea, being fast-growing legumes, contributes substantial biomass and biologically fixed nitrogen, which upon incorporation, enhances soil organic matter, nutrient mineralization and rhizosphere microbial activity. These processes improve nutrient synchronization with maize demand and strengthen root-soil interactions. These results are in line with some previous studies which reported improved maize vegetative growth under sun hemp intercropping systems (17, 18).

**Table 1.** Effect of nitrogen levels and green manure intercropping on growth parameters of maize at 90 DAS

Treatments	Plant height (cm)	Number of leaves	Leaf area (cm <sup>2</sup> )	Leaf area index (60- 90 DAS)	Total dry matter production (g plant <sup>-1</sup> )	CGR (60-90 DAS) (g m <sup>-2</sup> day <sup>-1</sup> )
<b>Main plot (N: Nitrogen levels)</b>						
N <sub>1</sub>	225.76	12.88	5678.57	3.16	257.41	30.50
N <sub>2</sub>	235.02	13.35	5949.11	3.31	269.60	31.18
N <sub>3</sub>	243.39	13.74	6223.52	3.46	282.04	32.03
S. Em. (±)	2.77	0.10	76.25	0.04	3.44	0.39
C.D. @ 5 %	10.87	0.39	299.41	0.17	13.50	1.53
<b>Subplots (I: Intercrops)</b>						
I <sub>0</sub>	228.61	12.96	5732.00	3.18	260.84	30.67
I <sub>1</sub>	237.25	13.47	6030.08	3.35	273.55	31.52
I <sub>2</sub>	233.81	13.26	5944.12	3.30	268.32	31.13
I <sub>3</sub>	239.22	13.62	6095.39	3.39	276.02	31.64
S. Em. (±)	1.71	0.10	50.20	0.04	2.55	0.33
C.D. @ 5 %	5.08	0.31	149.16	0.10	7.57	0.99
<b>Interaction (N×I)</b>						
N <sub>1</sub> I <sub>0</sub>	219.16	12.33	5411.90	3.01	247.91	29.94
N <sub>1</sub> I <sub>1</sub>	228.33	13.11	5775.61	3.21	261.53	30.76
N <sub>1</sub> I <sub>2</sub>	225.40	12.87	5683.63	3.16	256.77	30.52
N <sub>1</sub> I <sub>3</sub>	230.14	13.23	5843.16	3.25	263.43	30.80
N <sub>2</sub> I <sub>0</sub>	228.30	13.10	5759.27	3.20	261.14	30.64
N <sub>2</sub> I <sub>1</sub>	238.15	13.46	6014.34	3.34	273.47	31.46
N <sub>2</sub> I <sub>2</sub>	233.48	13.29	5931.89	3.30	267.83	31.02
N <sub>2</sub> I <sub>3</sub>	240.16	13.57	6090.94	3.38	275.97	31.58
N <sub>3</sub> I <sub>0</sub>	238.39	13.46	6024.84	3.35	273.48	31.43
N <sub>3</sub> I <sub>1</sub>	245.26	13.84	6300.30	3.50	285.66	32.33
N <sub>3</sub> I <sub>2</sub>	242.55	13.63	6216.84	3.45	280.37	31.85
N <sub>3</sub> I <sub>3</sub>	247.37	14.05	6352.08	3.53	288.65	32.53
S. Em. (±)	2.96	0.18	86.95	0.06	4.41	0.58
C.D. @ 5 %	8.79	0.53	258.35	0.18	13.12	1.72

**Note:** N1 - 75 % RDN; N2 -100 % RDN; N3 - 125 % RDN; I0 - Sole maize; I1 - Maize + Cowpea; I2 - Maize + Horse gram and I3 - Maize + Sun hemp; DAS: Days after sowing

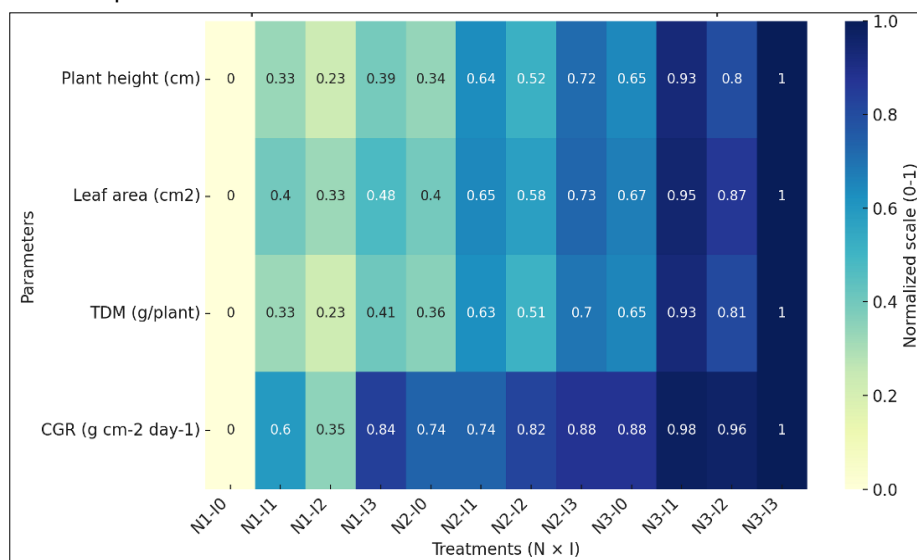
The N × I interaction was significant for all growth traits, with 125 % RDN + sun hemp (N<sub>3</sub>I<sub>3</sub>) showing the highest values, followed by N<sub>3</sub>I<sub>1</sub> and N<sub>3</sub>I<sub>2</sub>. The lowest growth occurred under 75 % RDN + sole maize (N<sub>1</sub>I<sub>0</sub>). This synergy arises from mineral and biologically fixed nitrogen, improved soil carbon and enhanced nutrient recycling. These results conform with some proved former reports which showed higher growth with maize + sun hemp intercropping, along with improved nitrogen application (19-21).

Heatmap rankings further confirmed N<sub>3</sub>I<sub>3</sub> as the most consistently superior combination (Fig. 3). The biomass returned by legumes contributes to long-term soil health by improving organic carbon and nutrient reserves-key sustainability gains in the nutrient-depleted sandy loam Alfisols of the Southern Telangana Zone (STZ). This reduced dependence on external fertilizers also strengthens system sustainability and lowers production costs for farmers.

**Yield parameters**

Yield attributes-cob length, cob girth, cob weight and grains per cob -were significantly influenced by nitrogen levels and intercropping systems (Table 2). Increasing N supply improved all yield components, with 125 % RDN producing significantly superior values, though often statistically comparable with 100 % RDN. Adequate nitrogen enhances grain set and filling by increasing assimilate availability (22-24).

Among intercrops, maize + sun hemp (I<sub>3</sub>) consistently recorded the highest yield attributes due to the combined contribution of biological N<sub>2</sub> fixation, nutrient recycling and improved soil physical conditions that promote root proliferation and nutrient uptake (17-18, 25).



**Fig. 3.** Heat map of maize growth parameters as influenced by green manure intercropping under varied levels of nitrogen.

**Table 2.** Effect of nitrogen levels and GM intercropping on yield parameters and yield of maize

Treatments	Cob length (cm)	Cob girth (cm)	Cob weight (g plant <sup>-1</sup> )	Number of grains per cob	Grain yield (kg ha <sup>-1</sup> )	Straw yield (kg ha <sup>-1</sup> )
<b>Main plot (N: Nitrogen levels)</b>						
N <sub>1</sub>	17.23	14.69	187.03	634.31	6035	7909
N <sub>2</sub>	17.93	15.25	203.90	692.95	6399	8313
N <sub>3</sub>	18.63	15.79	219.07	749.98	6735	8721
S. Em. (±)	0.23	0.19	3.88	17.88	90	106
C.D. @ 5 %	0.90	0.73	15.23	70.19	355	416
<b>Subplots (I: Intercrops)</b>						
I <sub>0</sub>	17.37	14.84	192.10	652.47	6097	7964
I <sub>1</sub>	18.15	15.39	207.34	707.27	6500	8443
I <sub>2</sub>	17.90	15.19	202.77	686.24	6390	8311
I <sub>3</sub>	18.30	15.55	211.12	723.67	6572	8540
S. Em. (±)	0.13	0.11	2.21	12.00	58	76
C.D. @ 5 %	0.39	0.33	6.56	35.66	171	226
<b>Interaction (N×I)</b>						
N <sub>1</sub> I <sub>0</sub>	16.60	14.22	172.99	589.17	5711	7500
N <sub>1</sub> I <sub>1</sub>	17.48	14.85	191.76	649.30	6157	8057
N <sub>1</sub> I <sub>2</sub>	17.26	14.67	187.33	632.67	6046	7928
N <sub>1</sub> I <sub>3</sub>	17.57	15.02	196.04	666.10	6227	8151
N <sub>2</sub> I <sub>0</sub>	17.33	14.94	193.21	655.89	6100	7984
N <sub>2</sub> I <sub>1</sub>	18.16	15.36	207.97	709.00	6514	8432
N <sub>2</sub> I <sub>2</sub>	17.87	15.22	202.50	684.50	6393	8293
N <sub>2</sub> I <sub>3</sub>	18.37	15.49	211.92	722.43	6589	8542
N <sub>3</sub> I <sub>0</sub>	18.18	15.37	210.11	712.37	6480	8406
N <sub>3</sub> I <sub>1</sub>	18.79	15.96	222.30	763.52	6830	8839
N <sub>3</sub> I <sub>2</sub>	18.58	15.68	218.47	741.55	6731	8712
N <sub>3</sub> I <sub>3</sub>	18.97	16.15	225.40	782.49	6900	8928
S. Em. (±)	0.22	0.19	3.83	20.79	100	132
C.D. @ 5 %	0.67	0.56	11.38	61.76	297	392

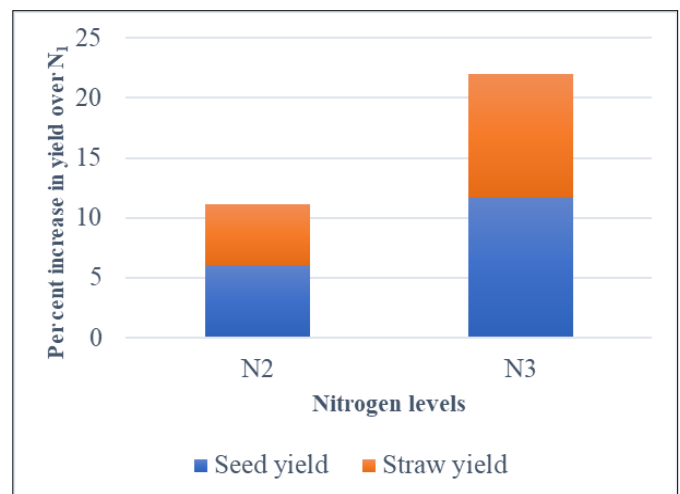
**Note:** N1 - 75 % RDN; N2 -100 % RDN; N3 - 125 % RDN; I0 - Sole maize; I1 - Maize + Cowpea; I2 - Maize + Horse gram and I3 - Maize + Sun hemp; DAS: Days after sowing

The interaction effect revealed that N<sub>3</sub>I<sub>3</sub> produced the highest yield attributes, confirming the cumulative benefit of mineral N and nutrient release from sun hemp biomass (19, 26-27). These improvements reflect enhanced internal nitrogen-use efficiency, contributing to both productivity and reduced external fertilizer dependence.

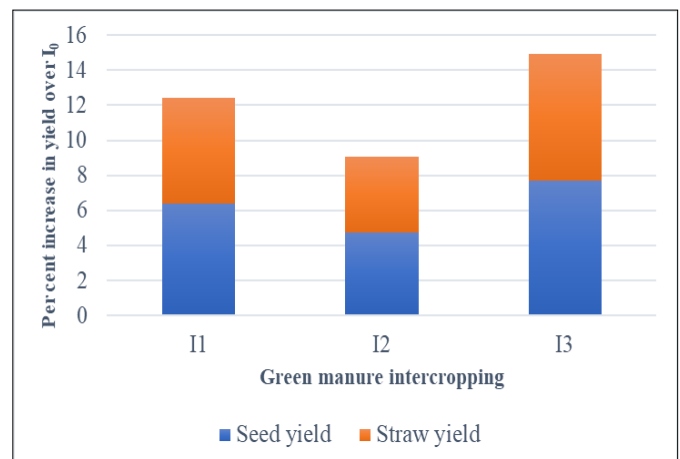
### Grain and straw yield

Grain and straw yields followed trends similar to growth and yield attributes (Table 2). 125 % RDN (N<sub>3</sub>) recorded the highest grain (6735 kg ha<sup>-1</sup>) and straw yield (8721 kg ha<sup>-1</sup>), though the marginal difference from 100% RDN suggests diminishing returns (28-29). The lowest yields occurred under 75% RDN due to inadequate vegetative growth and poor cob development. Increasing nitrogen from 75 per cent to 100 per cent RDN enhanced grain yield by 6.04 per cent, while 125 per cent RDN improved it by 11.61 per cent and 5.25 per cent over 75 per cent RDN and 100 per cent RDN, respectively. Application of 100 per cent and 125 per cent RDN resulted in 5.13 and 10.23 per cent higher straw yield respectively, over 75 per cent RDN (Fig. 4).

Among intercrops, maize + sun hemp (I<sub>3</sub>) recorded the highest yields, followed by maize + cowpea (I<sub>1</sub>). The improved yields with legume intercropping stem from enhanced nutrient supply, better soil aeration, active microbial processes and improved nutrient use efficiency (17, 26). Compared to sole maize, sun hemp intercropping gave a grain yield advantage of 7.80 per cent followed by cowpea (6.62%) and horse gram (4.80%) and also Maize + Sun hemp recorded 7.29 per cent higher straw yield compared to sole maize (Fig. 5).



**Fig. 4.** Per cent increase in yield over 75% RDN.



**Fig. 5.** Per cent increase in yield over sole maize.

The N × I interaction was significant, with N<sub>3</sub>I<sub>3</sub> producing the highest grain (6900 kg ha<sup>-1</sup>) and straw yields (8928 kg ha<sup>-1</sup>) and the lowest yields observed under N<sub>1</sub>I<sub>0</sub>. N<sub>3</sub>I<sub>3</sub> recorded 20.78 and 19.04 per cent higher grain and straw yield, respectively over N<sub>1</sub>I<sub>0</sub>, clearly demonstrating the synergistic effect of higher nitrogen and green manure intercropping (Fig. 6). Thus, green manure intercropping proved beneficial over sole maize with the magnitude of increase being more pronounced under sun hemp followed by cowpea.

These results highlight that integrating legumes not only enhances yield but also contributes to soil fertility restoration, reducing long-term fertilizer requirements and supporting sustainable intensification in the STZ.

Heatmaps also showed a clear gradient, with darker intensities in N<sub>3</sub>I<sub>3</sub> and the lightest shades in N<sub>1</sub>I<sub>0</sub> (Fig. 7). Cobs from maize + sun hemp visually indicated superior kernel filling across nitrogen levels (Fig. 8).

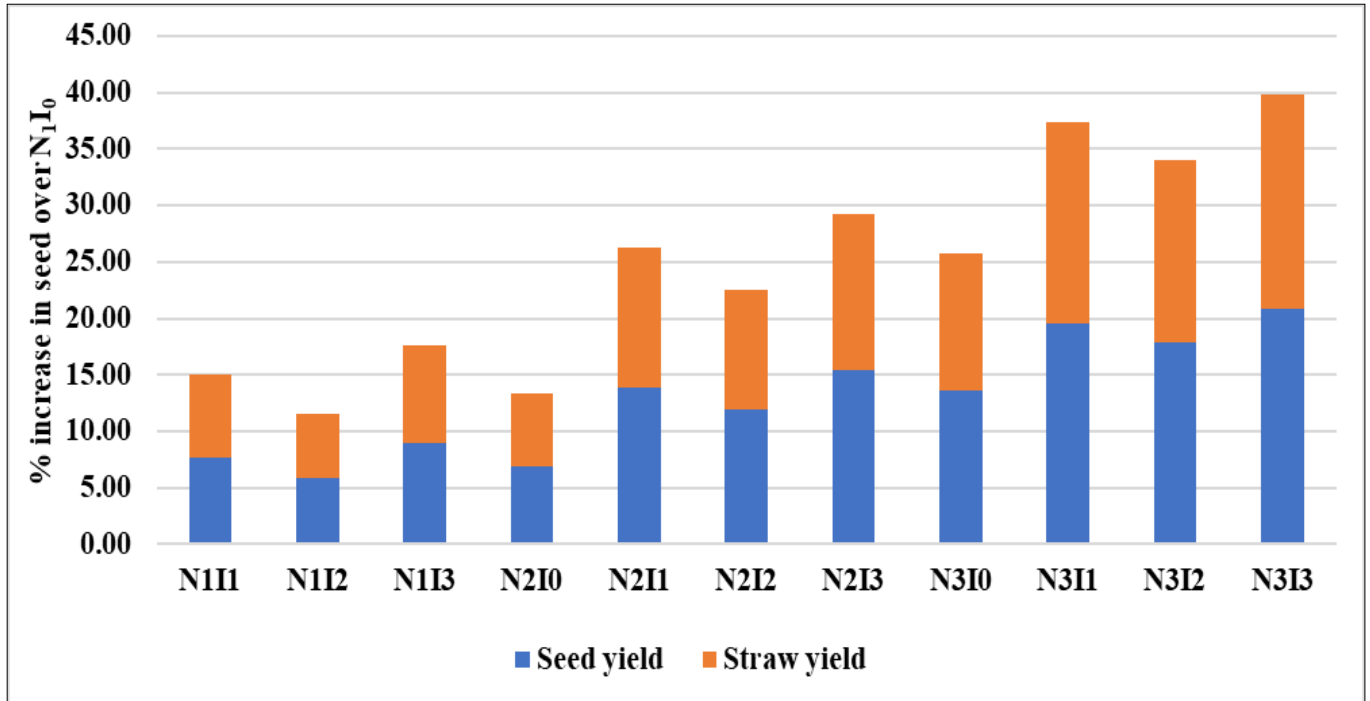


Fig. 6. Per cent increase in yield over 75% RDN with sole maize (N<sub>1</sub>I<sub>0</sub>).

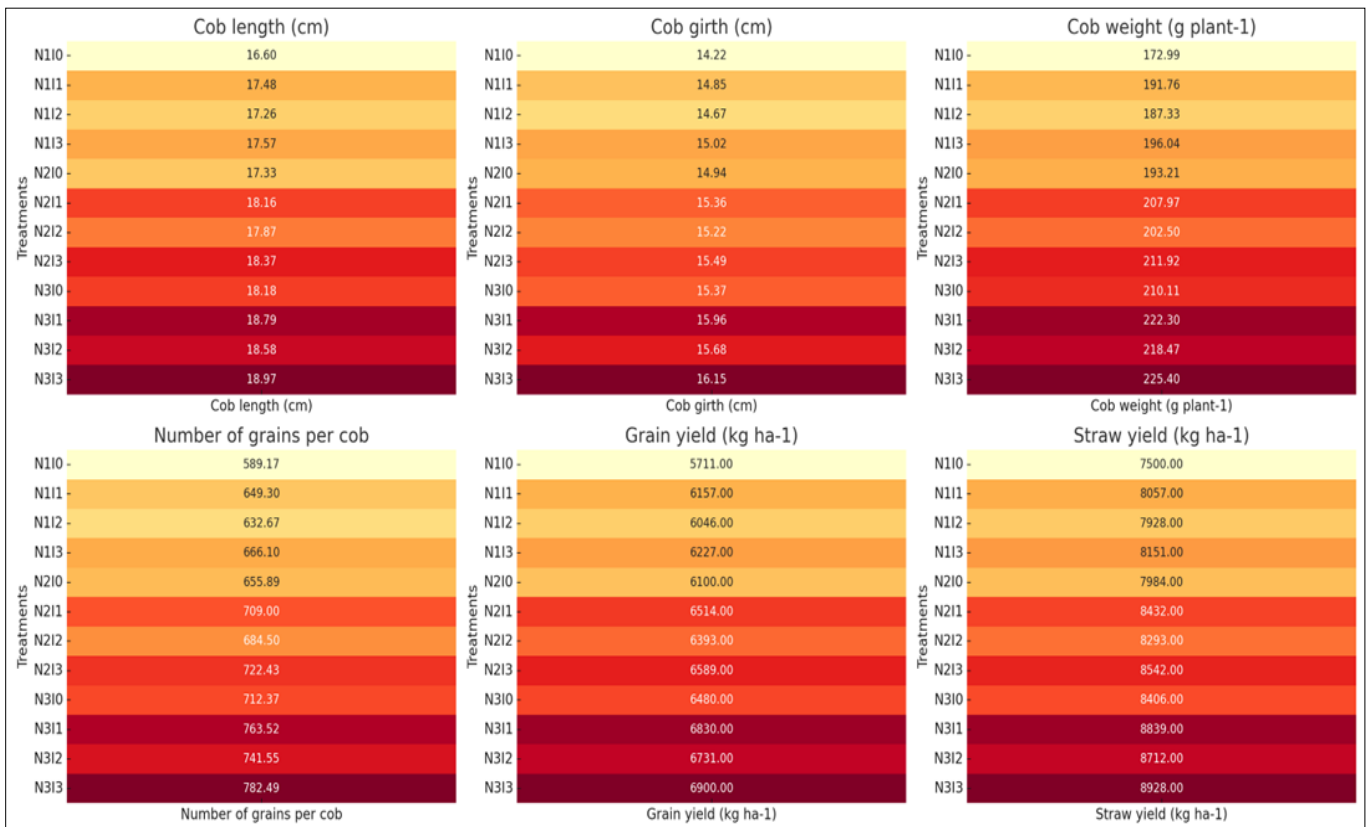
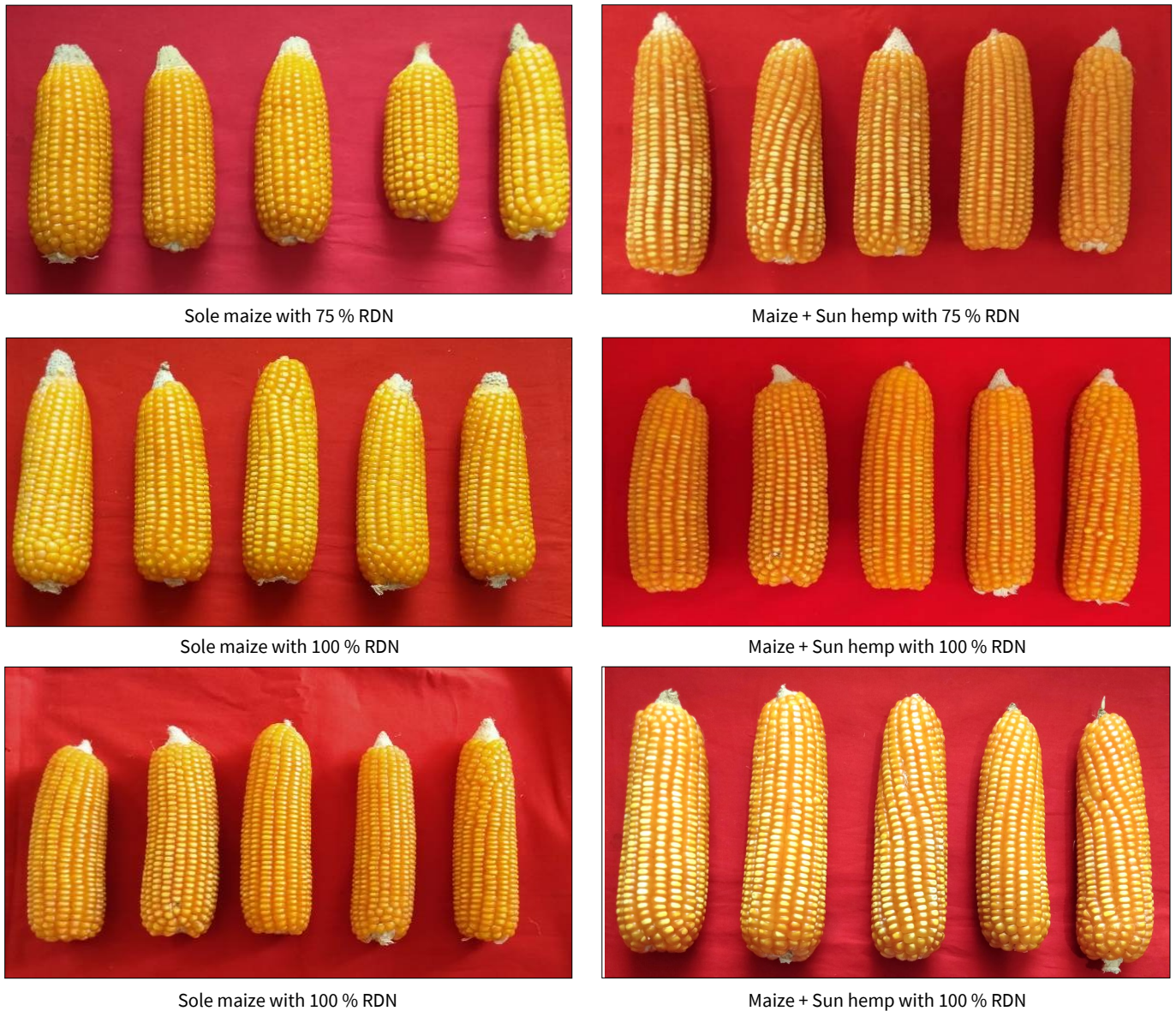


Fig. 7. Comparative heatmaps of yield parameters and yield of maize as influenced by green manure intercropping under varied levels of nitrogen.



**Fig. 8.** Comparison of cobs in sole maize and maize + sun hemp at varied nitrogen levels.

### Conclusion

Application of 100 % and 125 % Recommended dose of nitrogen of maize (RDN) significantly increased maize yield compared to 75% RDN, with only marginal gains beyond 100 %, indicating a plateau in nitrogen response. Green manure intercropping further enhanced yield, consistently following the order sun hemp > cowpea > horse gram, demonstrating the complementary role of legume biomass in strengthening nitrogen supply and improving overall crop performance. Yield advantage exceeded 20 % under higher N with green manure compared to 75 % RDN. Legume intercrops consistently outperformed sole maize, particularly sun hemp under optimal N management. The findings indicate that integrating legume green manure intercrops-particularly sun hemp-into a maize-maize system, combined with optimal nitrogen management, can enhance productivity while partially substituting chemical N inputs. This approach not only sustains or improves yields but also contributes to better soil health through increased organic matter, improved nutrient cycling and enhanced microbial activity. By reducing reliance on synthetic nitrogen fertilizers, the system also helps lower nutrient losses and the associated environmental footprint, making it a promising strategy for resilient and sustainable intensification in rainfed double-cropping systems.

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### Authors' contributions

VS and VHK carried out the field experiment and statistical analysis, GGK contributed to manuscript making, STM, TGN and GM helped in editing the manuscript. All authors read and approved the final manuscript.

### Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interests to declare.

**Ethical issues:** None

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