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LONG-TERM IMPACT OF TILLAGE PRACTICES AND PRECISION NUTRIENT MANAGEMENT ON PRODUCTIVITY, MAIZE EQUIVALENT YIELD, AND PROFITABILITY OF MAIZE IN RICE-MAIZE CROPPING SYSTEM

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ABSTRACT

A five-year field experiment (2019-20 to 2023-24) was conducted in a split-plot design with three replications. Main plots comprised three tillage practices: zero tillage (ZT), conventional tillage (CT), and permanent beds (PB). Sub-plots included three nutrient management strategies: recommended dose of fertilizers (RDF), site-specific nutrient management (SSNM), and 33% basal N + Green-Seeker-based nitrogen management (GS). Rice and maize grain yields, maize equivalent yield (MEY), net returns, and benefit-cost (B:C) ratios were analyzed. Zero tillage consistently recorded the highest rice grain yield (pooled mean: 5442 kg ha⁻¹) and maize grain yield (10,657 kg ha⁻¹), significantly outperforming CT and PB. Among nutrient management strategies, GS-based management produced the highest rice (4635 kg ha⁻¹) and maize (9709 kg ha⁻¹) yields. The ZT + GS combination achieved the highest system productivity with MEY of 14,893 kg ha⁻¹. Economic analysis revealed that permanent beds with GS management generated the maximum net returns (Rs. 1, 82,000 ha⁻¹), while ZT + GS recorded the highest B:C ratio (3.8). CT + RDF resulted in the lowest economic performance across all parameters. The integration of zero tillage with Green-Seeker-based precision nitrogen management significantly enhances productivity and profitability in rice-maize systems.

Keywords : Rice-maize system, Zero tillage, Green-Seeker, Site-specific nutrient management, Profitability.

Introduction

Rice-maize cropping systems have emerged as an important production system in South Asia, particularly in the Indo-Gangetic Plains, due to their high productivity and profitability potential (Gathala *et al.*, 2015). This cropping system combines the region's staple food grain (rice) with a high-value cash crop (maize), offering diversification opportunities and improved livelihoods for smallholder farmers. However, the sustainability of intensive rice-maize systems is increasingly threatened by declining soil health, escalating production costs, labor scarcity, and inefficient resource use (Jat *et al.*, 2019). Conventional tillage practices involving intensive soil manipulation through repeated ploughing and puddling have been

traditionally followed in rice-based systems. While these practices help in weed control and seedbed preparation, they lead to numerous adverse effects including soil structure deterioration, organic matter depletion, increased greenhouse gas emissions, and high energy and water requirements (Lal, 2015). In the rice-maize system, the transition from puddled transplanted rice to dry-seeded maize creates additional challenges related to soil physical conditions and water management (Humphreys *et al.*, 2016). Conservation agriculture-based tillage practices such as zero tillage and permanent beds offer potential solutions to these challenges. Zero tillage minimizes soil disturbance, preserves soil structure, enhances biological activity, and reduces production costs (Gathala *et al.*, 2011).

Permanent raised beds provide opportunities for improved water management, reduced compaction, and enhanced root growth (Sayre and Hobbs, 2004). However, the performance of these alternative tillage systems under diverse agro-ecological conditions and their long-term effects on system productivity need thorough evaluation. Parallel to tillage management, nutrient management remains a critical factor determining the productivity and sustainability of rice-maize systems. The traditional blanket application of recommended doses of fertilizers (RDF) often leads to inefficient nutrient use due to mismatch between nutrient supply and crop demand (Dobermann *et al.*, 2002). Nitrogen, being the most limiting nutrient in cereal production, requires careful management to minimize losses and maximize use efficiency. Site-Specific Nutrient Management (SSNM) approaches that consider indigenous nutrient supply, target yields, and location-specific factors have shown promise in improving nutrient use efficiency (Pampolino *et al.*, 2022). Recent advances in precision agriculture technologies, particularly optical sensors like Green-Seeker, offer opportunities for real-time, need-based nitrogen management. The Green-Seeker sensor measures the Normalized Difference Vegetation Index (NDVI), which correlates strongly with crop biomass and nitrogen uptake, enabling precise fertilizer application based on actual crop demand (Raun *et al.*, 2002; Ali *et al.*, 2017). This approach has demonstrated significant potential for improving nitrogen use efficiency and crop productivity in cereal systems (Bijay-Singh *et al.*, 2011; Sapkota *et al.*, 2021). Despite the individual benefits of conservation tillage and precision nutrient management, their combined effects in the rice-maize cropping system under long-term conditions remain inadequately documented. Furthermore, the economic viability of these practices, as reflected in net returns and benefit-cost ratios, is crucial for farmer adoption. The maize equivalent yield, which integrates the productivity of both crops in the system, provides a holistic measure of system performance. Therefore, this study was undertaken to evaluate the effect of different tillage and nutrient management practices on the grain yield of rice and maize, economics of maize and maize equivalent yield in rice-maize cropping system.

Materials and Methods

Experimental Site

The field experiment was conducted over five consecutive years from 2019-20 to 2023-24 at the research farm (Seed Farm) of Bidhan Chandra Krishi Viswavidyalaya located in Kalyani, Nadia district, West Bengal. The experimental site falls under the new

alluvial zone of West Bengal and is situated at 22°57' N latitude and 88°20' E longitude with an average altitude of 9.75 m above the mean sea level.

Experimental Design and Treatments

The experiment was laid out in a split-plot design with three replications. The treatments consisted of three tillage practices in the main plots viz. T₁: Zero Tillage, T₂: Conventional Tillage and T₃: Permanent Bed and three nutrient management strategies viz. N₁: Recommended Dose of Fertilizers (RDF), N₂: Site-Specific Nutrient Management (SSNM) and N₃: 33% N + Green Seeker Based Nitrogen Management in the sub-plots.

Data Collection

Grain Yield

At maturity, rice and maize crops were harvested from each net plot (excluding border rows). The harvested produce was threshed, cleaned, and weighed. Grain moisture content was determined using a moisture meter, and grain yield was expressed in kg ha⁻¹ at standard moisture levels (14% for rice, 15% for maize).

Maize Equivalent Yield

To compare the system productivity across treatments, maize equivalent yield (MEY) was calculated using the following formula:

$$\text{MEY (kg ha}^{-1}\text{)} = \text{Rice grain yield} \times (\text{Price of rice} / \text{Price of maize}) + \text{Maize grain yield}$$

Where prices were based on the minimum support price (MSP) or prevailing market prices for the respective years.

Economic Analysis

Cost of Cultivation: The total cost of cultivation for each treatment was calculated by considering all variable costs including land preparation, seed, fertilizer, plant protection chemicals, irrigation charges, labour costs, and harvesting/threshing expenses. The costs were computed based on prevailing wage rates and input prices during each year of study. Gross return, net return and B:C ratio were calculated by following formula-

Gross Returns: Gross returns were calculated by multiplying the grain yield with the minimum support price (MSP) or prevailing market price of the produce.

$$\text{Net Returns (Rs. ha}^{-1}\text{)} = \text{Gross Returns} - \text{Total Cost of Cultivation}$$

$$\text{B:C Ratio} = \text{Gross Returns} / \text{Total Cost of Cultivation}$$

All economic indicators were expressed in Indian Rupees (Rs.) per hectare.

Statistical Analysis

The data collected on various parameters over five years (2019-20 to 2023-24) were compiled and subjected to statistical analysis. The analysis of variance (ANOVA) technique appropriate for [factorial/split-plot] randomized complete block design was employed using [statistical software: e.g., SAS, SPSS, R, OPSTAT]. The significance of treatment effects was tested using the F-test at 5% probability level. Critical difference (CD) values at 5% level of significance were calculated for comparing treatment means where F-test was significant.

For pooled analysis over five years, the data were analysed using a combined analysis of variance technique considering years as random effects and treatments as fixed effects. The homogeneity of error variances across years was tested using Bartlett's test before performing pooled analysis.

Result and Discussion

Effect of Tillage Practices on Rice Grain Yield

The data presented in Table 1 reveals a significant effect of tillage practices on the grain yield of rice across all five years of the study (2019–20 to 2023–24) as well as in the pooled analysis. Among the tillage treatments, Zero Tillage (T1) consistently recorded the highest rice grain yield throughout the experimentation period. The pooled mean yield under zero tillage was 5442.40 kg ha⁻¹, which was substantially higher than both Conventional tillage (T2: 4145.20 kg ha⁻¹) and Permanent bed (T3: 4048.60 kg ha⁻¹).

The critical difference (CD) values at the 5% level of significance for tillage ranged from 301.0 to 402.0 across individual years, confirming that the yield differences between T1 and the other tillage practices were statistically significant. Notably, yields under Conventional tillage and Permanent bed were statistically comparable in most years, with the Permanent bed system recording the numerically lowest pooled yield (4048.60 kg ha⁻¹).

Effect of Nutrient Management on Rice Grain Yield

Regarding nutrient management strategies, the application of 33% N + Green Seeker based nitrogen management (N3) resulted in the highest rice grain yield across all years. The pooled data indicates that N3 produced an average yield of 4635.20 kg ha⁻¹, outperforming both the Site-Specific Nutrient Management (N2: 4359.20 kg ha⁻¹) and the State

Recommended Dose of Fertilizer (N1: 4188.40 kg ha⁻¹).

In the first year of the study (2019-20), the effect of nutrient management was non-significant (CD: NS). However, from 2020-21 onwards, the differences became statistically significant (CD ranging from 408.5 to 454.9). The SSNM (N2) consistently outperformed the RDF (N1), but remained inferior to the Green Seeker-based approach (N3)

Superiority of Zero Tillage in Rice Grain Yield

The significant increase in rice grain yield under zero tillage (T1) compared to conventional tillage (T2) and permanent beds (T3) are a key finding of this study. The yield advantage of zero tillage (approximately 1300 kg ha⁻¹ higher pooled mean than CT) can be attributed to several soil-plant-water relations. Firstly, zero tillage minimizes soil disturbance, which preserves soil macro-pores and enhances the activity of earthworms and beneficial microorganisms (Lal, 2015). This leads to improved infiltration and water retention, which is critical for rice, particularly during aerobic phases or dry spells. Secondly, the retention of crop residues under zero tillage (common in rice-maize systems) moderates soil temperature and reduces evaporative loss, creating a favorable microclimate for root proliferation (Gathala *et al.*, 2011).

The relatively poor performance of the Permanent bed (T3) system in this specific dataset is interesting. While permanent beds are often advocated for upland crops like maize, they can sometimes lead to higher bulk density in the furrows or poor puddling effects in transplanted rice if beds are disturbed, potentially explaining the lower yields observed here relative to zero tillage (Jat *et al.*, 2014).

Precision Nutrient Management: The Green Seeker Advantage on Rice Grain Yield

The consistent and significant yield response to the N3 treatment (33% N + Green Seeker based N management) underscores the importance of matching nitrogen supply with crop demand. The Green Seeker optical sensor measures the Normalized Difference Vegetation Index (NDVI), which correlates strongly with crop biomass and N uptake (Ali *et al.*, 2017).

The relatively poor performance of the blanket RDF (N1) suggests that fixed-time, fixed-dose N application leads to nitrogen losses (via volatilization, denitrification, and leaching) in the rice ecosystem. The SSNM (N2) improved yields over RDF by accounting for indigenous nutrient supply, but the Green Seeker approach (N3) provided the additional

benefit of "real-time" N management. By applying the majority of N (33% basal + rest via sensor) based on the actual crop health, farmers can apply nitrogen during the critical growth stages (e.g., panicle initiation), leading to higher spikelet fertility and grain filling (Singh *et al.*, 2019).

Table 1: Effect of Nutrient management in rice-maize cropping system under different tillage practices on rice grain yield

Treatment	Rice Grain Yield (kg ha ⁻¹)					
	2019-20	2020-21	2021-22	2022-23	2023-24	Pooled
Tillage Practices						
T1:Zero tillage	5277	5330	5502.00	5429.00	5674.00	5442.40
T2:Conventional tillage	3900	3904	3743.00	5113	4066.00	4145.20
T3:Permanent bed	3748	3755	3793.00	5036	3911.00	4048.60
CD at 5 %	400	402.0	380.90	301.0	392.80	
Nutrient Management						
N1:RDF (120:60:60)	4119	4140	4182.00	4189	4312.00	4188.40
N2:SSNM (120:44:51)	4229	4250	4412.00	4356	4549.00	4359.20
N3:33% N+ Green seeker based	4576	4598	4644.00	4569	4789.00	4635.20
CD at (5%)	NS	454.9	408.50	412.0	421.20	

Effect of Tillage Practices on Maize Grain Yield

Tillage practices exerted a significant influence on maize grain yield across all five experimental years and in the pooled analysis (Table 2). Zero tillage (T1) consistently recorded the highest maize yields, with a pooled mean of 10,656.80 kg ha⁻¹. This was followed by conventional tillage (T2: 9055.67 kg ha⁻¹), while the permanent bed system (T3) produced the lowest yields (pooled mean: 7436.49 kg ha⁻¹). The critical difference (CD) values for tillage (ranging from 522.9 to 609.6 kg ha⁻¹) confirm that the yield differences among tillage treatments were statistically significant ($p < 0.05$) in each year.

Effect of Nutrient Management on Maize Grain Yield

Nutrient management strategies also had a marked effect on maize productivity. Across the pooled data, Green Seeker-based N management (N3: 33% N basal + sensor-guided top-dressing) resulted in the highest grain yield (9709.14 kg ha⁻¹). Interestingly, the performance of the State Recommended Dose of Fertilizer (N1: RDF) and Site-Specific Nutrient Management (N2: SSNM) varied over the years. In the initial three years (2019–20 to 2021–22), SSNM (N2) out-yielded RDF (N1). However, in 2022–23 and 2023–24, RDF produced substantially higher yields than SSNM, and even exceeded the Green Seeker treatment in those two specific years. The pooled means indicate that overall, N3 was superior, followed by N1 (8875.10 kg ha⁻¹) and N2 (8565.67 kg ha⁻¹). All nutrient management effects were statistically significant (CD values ranging from 659.4 to 768.9 kg ha⁻¹) in every year.

Zero Tillage Enhances Maize Productivity

The consistent superiority of zero tillage (T1) for maize grain yield is a striking result. The yield advantage of ~1600 kg ha⁻¹ over conventional tillage can be attributed to several mechanisms. Firstly, zero tillage with residue retention improves soil aggregation and organic matter content in the surface layer, leading to better water infiltration and moisture conservation during the maize growing season (Jat *et al.*, 2020). Secondly, zero tillage allows for earlier sowing of maize after rice harvest, enabling the crop to escape terminal heat stress and capture more growing degree days (Gathala *et al.*, 2015).

Nutrient Management Dynamics: Sensor-Based N is Superior

The overall highest pooled yield under Green Seeker-based N management (N3) reinforces the value of precision nitrogen technologies in maize. Maize has a high N demand and is highly responsive to split applications. The Green Seeker sensor, by measuring NDVI, allows for real-time adjustment of N rates based on crop vigor and biomass, leading to optimized N uptake, increased kernel number per cob, and higher test weight (Raun *et al.*, 2002; Bijay-Singh *et al.*, 2011). The sensor-guided approach likely reduced N losses and improved nitrogen use efficiency (NUE) compared to blanket recommendations.

The inconsistent performance of SSNM (N2) relative to RDF (N1) requires careful interpretation. SSNM is designed to account for indigenous nutrient supply and match fertilizer application to site-specific yield goals. In the first three years, SSNM outperformed RDF, which is consistent with the expected benefits of balanced fertilization (Dobermann

et al., 2002). However, the dramatic reversal in 2022–23 and 2023–24, where RDF yields surged while SSNM yields declined, is unusual. This could be due to an interaction with tillage (not displayed in the main effects table) or a change in soil nutrient status. It is possible that the RDF plots received a higher cumulative P and K input over time, leading to a build-

up of these nutrients that benefited maize in later years. Alternatively, a seasonal pest or disease incidence may have differentially affected the SSNM plots. Since the CD values are consistent, these fluctuations are statistically robust but warrant further investigation through interaction analysis and soil test data.

Table 2: Effect of Nutrient management in rice-maize cropping system under different tillage practices on maize grain yield.

Treatment	Maize Grain Yield (kg ha ⁻¹)					
	2019-20	2020-21	2021-22	2022-23	2023-24	Pooled
Tillage Practices						
T1:Zero tillage	9782.00	10564.00	10352.80	11181.00	11405.00	10656.80
T2:Conventional tillage	8312.00	8977.00	8797.36	9501.00	9691.00	9055.67
T3:Permanent bed	6826.00	7372.00	7224.46	7802.00	7958.00	7436.49
CD at 5 %	522.90	564.70	553.47	597.70	609.60	
Nutrient Management						
N1:RDF (120:60:60)	7256.00	7836.00	7679.52	10695.00	10909.00	8875.10
N2:SSNM (120:44:51)	8307.00	8972.00	8792.36	8294.00	8460.00	8565.67
N3:33% N+ Green seeker based	9356.00	10105.00	9902.74	9496.00	9686.00	9709.14
CD at (5%)	659.40	712.20	697.89	753.80	768.90	

Effect of Tillage on net return

Among the tillage practices, the Permanent Bed system recorded the highest net return across all nutrient management treatments. This was followed by Zero Tillage, while Conventional Tillage consistently resulted in the lowest net returns, regardless of the nutrient source applied.

Effect of Nutrient Management on net return

Irrespective of the tillage system, precision-based nutrient management strategies outperformed the blanket recommendation (RDF). Site-Specific Nutrient Management (SSNM) and GreenSeeker (GS) based nutrient management achieved the highest net returns. The GS-based management generally showed a marginal advantage over SSNM under permanent beds and zero tillage. RDF (Recommended Dose of Fertilizers) recorded the lowest net return within each tillage category.

The variation in net return is a function of both the cost of cultivation and the grain yield obtained.

1. Superiority of Conservation Tillage (Permanent Bed and Zero Tillage):

The higher net returns under Permanent Bed and Zero Tillage can be attributed to two primary factors: -
Reduced Cost of Cultivation: These systems eliminate or reduce tillage operations, leading to significant savings in fuel, labor, and machinery costs compared to Conventional Tillage. **Yield Enhancement:** Permanent beds improve soil structure, aeration, and

root proliferation. They also facilitate better drainage and moisture conservation, leading to higher maize equivalent yields over the 5-year period.

2. Performance of Precision Nutrient Management (SSNM and GS based):

The higher net returns under SSNM and GreenSeeker treatments are driven by increased productivity rather than reduced input costs. -
Efficiency: Unlike RDF, which applies a fixed rate of nitrogen, SSNM and GS-based scheduling apply nitrogen based on the crop's demand and the inherent soil supply. This synchrony minimizes nitrogen losses (leaching/denitrification) and maximizes the yield response per unit of fertilizer applied.

Green Seeker Advantage: The GS-based approach uses a vegetation index (NDVI) to assess crop health in real-time and prescribe the exact dose of nitrogen required. This avoids over-fertilization and under-fertilization, optimizing the trade-off between input cost and yield, thereby maximizing the gross returns.

3. Poor Performance of Conventional Tillage + RDF: The combination of Conventional Tillage and RDF represents the traditional "business as usual" scenario. It incurs high operational costs (multiple plowings) and often leads to inefficient nutrient use due to split application schedules that do not align with the critical growth stages of the crop. This results in lower yields and higher costs, ultimately depressing the net return.

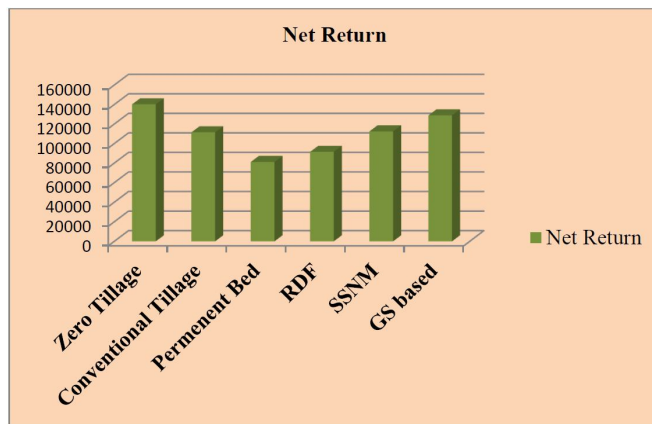


Fig. 1: Effect of Nutrient management in rice-maize cropping system under different tillage practices on net return (Rs. ha⁻¹) of maize (5 years Pooled data)

Effect of Tillage on B: C ratio of maize

Tillage practices exhibited a pronounced effect on the B:C ratio when averaged across nutrient management treatments. Zero Tillage recorded the highest B:C ratio (3.8), indicating superior economic efficiency and maximum profitability per unit of investment. Permanent Bed and Conventional Tillage systems followed, with identical B:C ratios of 3.4, suggesting comparable economic performance between these two tillage methods.

Effect of Nutrient Management on B: C of maize

Across all tillage systems, precision-based nutrient management strategies demonstrated clear economic advantages over blanket fertilizer recommendations. GS-based nutrient management achieved the highest B: C ratio (3.7), reflecting optimal resource utilization and maximum returns on fertilizer investment. SSNM followed with a B:C ratio of 3.3, showing substantial improvement over conventional practices. The RDF treatment recorded the lowest B:C ratio (2.9), indicating inferior economic efficiency and suboptimal conversion of inputs into revenue.

The Benefit-Cost ratio integrates both the cost of cultivation and the gross returns, providing a holistic measure of economic performance. The variations observed in Fig-2 can be comprehensively explained through the lens of input cost savings, yield enhancement, and resource use efficiency.

1. Superior Economic Efficiency of Zero Tillage

The highest B:C ratio under Zero Tillage (3.8) can be attributed to substantial reductions in production costs. Zero Tillage eliminates multiple tillage operations, resulting in significant savings on fuel, labor, and machinery maintenance compared to Conventional Tillage. These cost reductions directly enhance the B: C ratio, even if absolute yields are

comparable to other systems. Research across the Indo-Gangetic Plains has consistently demonstrated that zero tillage in maize-based systems reduces cultivation costs by approximately 15-20% while maintaining or slightly improving yields, thereby improving profitability. The slightly lower B:C ratio for Permanent Beds (3.4), despite potentially higher yields, reflects the higher initial investment and maintenance costs associated with bed planting .

2. Precision Nutrient Management Enhances Economic Returns

The superior performance of GS-based (3.7) and SSNM (3.3) over RDF (2.9) underscores the economic importance of matching nutrient supply with crop demand.

Green Seeker (GS-based) Technology: The real-time, sensor-based nitrogen management achieved the highest B:C ratio across all treatments. This aligns with recent findings in cereal systems where GreenSeeker-guided nitrogen application improved the B:C ratio by 18-24% compared to blanket RDF. The optical sensor measures the Normalized Difference Vegetation Index (NDVI), which correlates strongly with crop biomass and nitrogen demand, enabling precise fertilizer application only when and where needed. This precision prevents both over-application (wasted input cost) and under-application (yield loss), optimizing the relationship between input expenditure and output revenue. Studies have documented nitrogen savings of 15-20% with sensor-based management while simultaneously increasing grain yield by approximately 10-18% compared to RDF.

Site-Specific Nutrient Management (SSNM): The SSNM approach, which considers indigenous nutrient supply and target yield, recorded a B:C ratio of 3.3. Meta-analyses across multiple cropping systems have shown that SSNM increases profitability by an average of 15% while applying 10-15% less fertilizer nitrogen than farmer practice. By tailoring nutrient applications to specific field conditions and crop requirements, SSNM avoids the inefficiencies inherent in blanket recommendations. The principle of balancing nitrogen, phosphorus, potassium, and micronutrients based on site-specific deficiencies ensures that each unit of fertilizer contributes maximally to yield formation.

3. Inefficiency of Blanket Recommendation (RDF)

The RDF treatment recorded the lowest B:C ratio (2.9), representing a classic case of the "low efficiency, high cost" syndrome. Blanket recommendations, typically developed at regional or state levels, fail to account for spatial variability in soil fertility and

temporal variability in crop demand. This often results in nitrogen over-application during periods of low crop demand (leading to luxury consumption and leaching losses) or under-application during peak demand periods (leading to yield penalties). The resultant yields are suboptimal relative to the fertilizer investment, depressing the B:C ratio and reducing overall farm profitability. Furthermore, inefficient nitrogen use under RDF contributes to environmental pollution through nitrate leaching and nitrous oxide emissions.

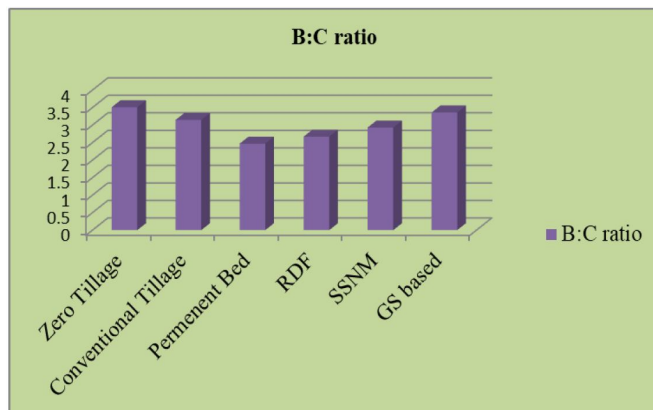


Fig. 2: Effect of Nutrient management in rice-maize cropping system under different tillage practices on B: C of maize (5 years Pooled data)

Performance of Tillage Practices on Maize equivalent yield: Among the tillage practices, Zero Tillage demonstrated the highest yield potential, with a maximum MEY of 22,500 kg/ha and a high median value of 21,000 kg/ha. This aligns with global meta-analyses reporting that no-tillage systems can significantly enhance grain yield in maize cropping systems compared to conventional tillage. However, Zero Tillage also showed a wide interquartile range, indicating some inter-annual variability in its performance. In contrast, Conventional Tillage and Permanent Bed systems produced lower median yields of 17,000 kg/ha and 16,050 kg/ha, respectively. The relatively lower performance of permanent beds in this study contrasts with some findings from semi-arid regions where permanent beds increased maize yields by over 70% compared to conventional tillage, suggesting that the benefits of specific tillage practices can be highly location-specific and dependent on interactions with other management factors like residue retention and climate.

Performance of Nutrient Management Strategies on Maize equivalent yield: When examining nutrient management, the GS based (GreenSeeker-based) nutrient management strategy was a top performer, achieving the highest maximum yield of 20,000 kg/ha

and the highest median yield of 19,500 kg/ha. This finding is consistent with field studies on spring maize in Nepal, where Green-Seeker-guided nitrogen application resulted in 17.35-45.81% higher grain yield than the recommended dose of fertilizers (RDF). The RDF and SSNM (Site-Specific Nutrient Management) strategies showed similar and consistent performance, with median yields around 17,500-17,800 kg/ha. These results underscore the effectiveness of precision nutrient management tools in optimizing nitrogen application based on real-time crop demand.

The superior performance of Zero Tillage can be explained by the gradual improvement in soil physical and biological properties. Over five years, the absence of tillage promotes the accumulation of soil organic matter, enhances soil aggregation, and improves water infiltration and retention. Research on the Loess Plateau has demonstrated that no-tillage practices significantly increase soil water storage in the 0-200 cm profile during both fallow and growing seasons, leading to higher relative chlorophyll content (SPAD values) and ultimately improved crop yields. Furthermore, conservation tillage practices have been shown to positively influence soil microbial communities and their nutrient cycling functions, with metagenomic analyses revealing higher abundances of genes associated with carbon, nitrogen, and phosphorus cycling under reduced tillage intensity.

The lower yields observed under Conventional Tillage are likely due to the continuous disturbance of soil structure, which can lead to the formation of hard pans, accelerated oxidation of organic matter, and higher moisture loss, ultimately stressing the crops. While some short-term studies in specific locations (e.g., northern hill zone of India) have reported superior wheat productivity under conventional tillage, the long-term pooled data from this study demonstrates the advantage of conservation tillage in a rice-maize system, consistent with findings from the Indo-Gangetic Plains.

Regarding nutrient management, the clear advantage of GS-based nutrient application highlights the importance of precision agriculture technologies. By synchronizing nitrogen application with the real-time requirements of the crop, the Green-Seeker sensor optimizes nitrogen use efficiency. Studies have demonstrated that active-optical sensors using NDVI can effectively predict corn grain yield and guide in-season nitrogen fertilization. In Nepal, Green-Seeker-based N management (143 kg N ha⁻¹) produced significantly higher grain yield and agronomic efficiency of nitrogen (21.30-27.82 kg grain kg⁻¹ N) compared to recommended dose fertilization (12.15 kg

grain kg^{-1} N). The fact that GS-based management performed best under Zero Tillage suggests a synergistic effect: the improved soil moisture and structure under zero tillage likely amplified the crop's response to precisely timed nitrogen applications.

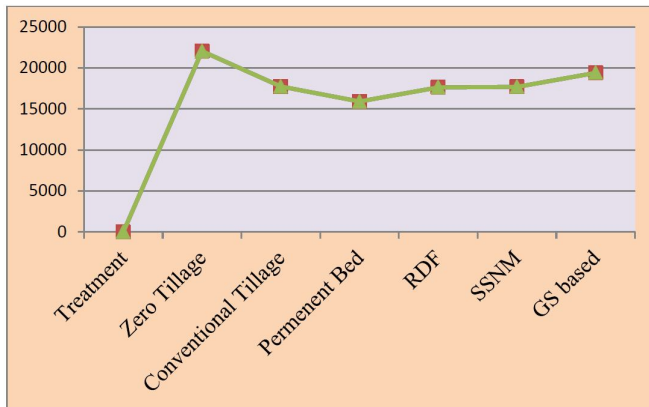


Fig. 3: Effect of Nutrient management in rice-maize cropping system under different tillage practices on Maize Equivalent Yield (kg ha^{-1}) (5 years Pooled data)

Conclusion

The five-year field experiment conclusively demonstrates that the integration of conservation tillage with precision nutrient management significantly enhances productivity, profitability, and sustainability of maize in rice-maize cropping systems. Zero tillage consistently outperformed conventional tillage and permanent beds, recording the highest rice (5442 kg ha^{-1}) and maize ($10,657 \text{ kg ha}^{-1}$) grain yields. Among nutrient management strategies, Green Seeker-based precision nitrogen management proved superior, producing maximum rice (4635 kg ha^{-1}) and maize (9709 kg ha^{-1}) yields by synchronizing nitrogen application with crop demand through real-time NDVI monitoring.

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