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Interactive effects of conservation tillage and biochar-based nutrient management on growth, yield and resource-use efficiency of maize (*Zea mays* L.)

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Abstract

A field experiment was conducted during the kharif season of 2025 at the Experimental Farm of the School of Agricultural Sciences, Malla Reddy University, Hyderabad, to evaluate the interactive effects of conservation tillage and biochar-based nutrient management on growth, productivity, and resource-use efficiency of maize (*Zea mays* L.) under semi-arid conditions. The experiment was laid out in a split-plot design with three replications, comprising three tillage systems in main plots—permanent bed with residue retention, zero tillage with residue retention, and conventional tillage—and four nutrient management treatments in sub-plots, namely 100% recommended dose of fertilizers (RDF), biochar at 2 t ha⁻¹, 100% RDF + biochar, and 75% RDF + biochar. Results revealed that conservation tillage practices significantly enhanced growth parameters, with permanent bed systems recording higher plant height, leaf area index, and dry matter accumulation compared to conventional tillage. Among nutrient treatments, the integrated application of 100% RDF with biochar resulted in superior growth and yield attributes. Grain yield was maximized under permanent bed systems (6477 kg ha⁻¹), while the combined application of RDF and biochar produced the highest grain yield (7383 kg ha⁻¹) and stover yield. Notably, the application of 75% RDF with biochar achieved comparable yields to 100% RDF, indicating the potential for reducing chemical fertilizer inputs without compromising productivity. This findings demonstrate that the integration of conservation tillage, particularly permanent bed planting, with biochar-based nutrient management significantly improves crop performance and resource-use efficiency. This approach offers a sustainable strategy for enhancing maize productivity under semi-arid agro-ecosystems.

Keywords: Conservation tillage, biochar, maize (*Zea mays* L.), crop productivity, sustainable agriculture

Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops globally, valued for its high productivity and wide adaptability across diverse agro-climatic conditions (Wang *et al.*, 2025) [23]. It plays a crucial role in the food, feed and industrial sectors, contributing significantly to food security and rural livelihoods, particularly in South Asia (Erenstein *et al.*, 2022; Padhan *et al.*, 2024) [4, 18]. In India, maize ranks as the third most important cereal crop, cultivated over 84.3 million hectares with a production of 248.4 million tonnes and an average productivity of 2947 kg ha⁻¹. In Telangana, it occupies 2.12 million hectares with a productivity of 4814 kg ha⁻¹, highlighting its growing economic importance (DA & FW, 2024–25) [5]. Maize production systems have undergone substantial transformation over time, driven by technological advancements and changing global demands. The introduction of high-yielding varieties during the Green Revolution significantly enhanced productivity. However, increasing ecological constraints such as land degradation, water scarcity and climate change continue to challenge sustainable maize production (Grote *et al.*, 2021) [7]. Conventional tillage practices, characterized by repeated soil disturbance, residue removal and sole dependence on chemical fertilizers, accelerate the depletion of soil organic carbon, degrade soil structure and reduce microbial activity, ultimately lowering input use efficiency (Srivastava *et al.*, 2025) [22]. In addition, continuous use of recommended doses of fertilizers without organic supplementation leads to nutrient imbalances, poor nutrient use efficiency and higher losses through leaching and

volatilization (Kumar *et al.*, 2021) ^[14]. These challenges are particularly severe under semi-arid tropical conditions, where low organic matter and erratic rainfall further constrain soil fertility and crop productivity (Meena *et al.*, 2023) ^[17].

In this context, conservation agriculture has emerged as a promising strategy to address these limitations. Practices such as permanent bed planting and zero tillage with residue retention minimize soil disturbance, improve soil aggregation, enhance moisture conservation and promote carbon sequestration (Jat *et al.*, 2023; Lal *et al.*, 2020) ^[10, 15]. Concurrently, integrated nutrient management approaches incorporating organic amendments like biochar provide additional benefits by improving soil cation exchange capacity, water holding capacity and microbial activity. Biochar, a stable carbon-rich material, enhances nutrient retention and contributes to long-term soil fertility and sustainability (Liu *et al.*, 2021; Zhang *et al.*, 2022) ^[16, 24]. The integration of conservation tillage with biochar-based nutrient management offers a sustainable pathway to improve soil health, enhance nutrient use efficiency and mitigate environmental impacts, including greenhouse gas emissions (Kiani *et al.*, 2024; Ibrahim *et al.*, 2020) ^[12, 9]. However, information on the interactive effects of tillage systems and nutrient management practices under field conditions in maize, particularly in semi-arid tropical regions, remains limited. Therefore, the present study was undertaken to evaluate the combined influence of different tillage systems and nutrient management practices on soil fertility, nutrient uptake, crop productivity and sustainability of kharif maize.

Materials and Methods

The field experiment was conducted during the *kharif* season of 2025 at Field No. A- 2, Experimental Farm, School of Agricultural Sciences, Malla Reddy University, Hyderabad, Telangana, India. The experimental site is located at 17°33' N latitude and 78°27' E longitude, at an altitude of 583 m above mean sea level. The region falls under a semi-arid tropical climate with a hot and humid kharif season. During the crop growth period, the mean maximum and minimum temperatures were 30.8 °C and 24.2 °C, respectively, with an average relative humidity of 72%. The experimental soil was alkaline in reaction with a pH of 8.03.

The experiment was laid out in a split-plot design with three replications, comprising 12 treatment combinations. The main plot treatments included three tillage and residue management practices: (i) permanent bed with crop residue retention, (ii) zero tillage with crop residue retention, and (iii) conventional tillage. The sub-plot treatments consisted of four nutrient management levels: (i) 100% recommended dose of fertilizers (RDF), (ii) biochar @ 2.0 t ha⁻¹, (iii) 100% RDF + biochar @ 2.0 t ha⁻¹, and (iv) 75% RDF + biochar @ 2.0 t ha⁻¹. The gross plot size was 5.4 m × 4.0 m, while the net plot size was 4.2 m × 3.6 m.

Maize hybrid 'Caspian 666' was used as the test crop. Sowing was carried out with a seed rate of 20 kg ha⁻¹ and spacing of 60 cm × 20 cm. The recommended dose of fertilizers (RDF) comprising 240 kg N, 80 kg P₂O₅, and 80 kg K₂O ha⁻¹ was applied through urea (46% N), diammonium phosphate (DAP; 18% N and 46% P₂O₅), and muriate of potash (MOP; 60% K₂O), respectively. The entire dose of phosphorus and potassium was applied as basal at the time of sowing, while nitrogen was applied in split doses, with a portion applied at sowing and the remaining in two equal splits at critical growth stages. Biochar was applied at the rate of 2.0 t ha⁻¹ in the designated treatments and incorporated into the soil prior to sowing. All other agronomic practices were followed uniformly across treatments

to ensure optimal crop growth and development.

Observations on growth parameters, including plant height, leaf area index (LAI), and dry matter production, were recorded from ten randomly selected plants in each net plot, and the mean values were computed. At maturity, the crop was harvested and manually threshed. Grain yield and stover yield were recorded from each net plot and converted to kg ha⁻¹.

The experimental data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design, following the procedure outlined by Gomez and Gomez (1984) ^[6]. The significance of treatment effects was tested at the 5% probability level ($P \leq 0.05$). Differences between treatment means were compared using the least significant difference (LSD) test, and main plot and sub-plot effects were analyzed separately.

Results and Discussion

Effect of tillage and nutrient management on growth parameters of kharif maize

Growth parameters of kharif maize, namely plant height, leaf area index (LAI) and dry matter production, were significantly influenced by tillage and nutrient management practices (Table 1). Among tillage practices, permanent bed (PB) recorded significantly higher plant height (197.92 cm), LAI (2.73) and dry matter production (282.59 g plant⁻¹), followed by zero tillage (ZT) (188.83 cm, 2.52 and 252.80 g plant⁻¹, respectively), whereas the lowest values were observed under conventional tillage (CT) (163.23 cm, 2.35 and 220.87 g plant⁻¹, respectively). Nutrient management treatments also exerted a significant effect on growth attributes. The treatment 100% RDF + biochar @ 2 t ha recorded the highest plant height (202.14 cm), LAI (3.09) and dry matter production (291.79 g plant⁻¹), followed by 75% RDF + biochar @ 2 t ha⁻¹ (198.46 cm, 2.80 and 261.67 g plant⁻¹, respectively). In contrast, biochar alone resulted in the lowest values (141.67 cm, 1.75 and 201.26 g plant⁻¹), while 100% RDF alone showed intermediate performance (191.04 cm, 2.53 and 253.63 g plant⁻¹).

The interaction between tillage and nutrient management was non-significant for all growth parameters. The superior performance under conservation tillage (permanent bed and zero tillage) may be attributed to reduced soil disturbance, improved soil structure and aggregation, and enhanced moisture conservation, which collectively promoted better root proliferation and nutrient uptake (Jat *et al.*, 2023; Lal *et al.*, 2020) ^[10, 15]. The enhanced growth observed under combined application of biochar and fertilizers may be ascribed to the synergistic effect of balanced nutrient supply and the soil-conditioning properties of biochar, which improved nutrient availability, increased cation exchange capacity and stimulated shoot elongation (Adekiya *et al.*, 2023) ^[1]. The higher LAI under these treatments could be due to improved nutrient retention, reduced leaching losses and prolonged photosynthetic activity (Liu *et al.*, 2021; Zhang *et al.*, 2022) ^[16, 24]. In addition, the porous structure and high surface area of biochar likely improved soil moisture retention and rhizosphere conditions, thereby supporting greater leaf expansion (Sailaja *et al.*, 2023; Jiang *et al.*, 2022) ^[20, 11]. Similarly, increased dry matter production may be linked to improved canopy development, enhanced light interception and greater assimilate accumulation throughout the crop growth period (Bolan *et al.*, 2023) ^[2]. The combined influence of conservation tillage and biochar application likely improved soil physical and chemical properties, facilitating better root growth and nutrient uptake efficiency (Haider *et al.*, 2022; Kiani *et al.*, 2024) ^[8, 12]. These results are in conformity with earlier findings reporting

significant increases in biomass accumulation in maize under integrated soil and nutrient management practices (Haider *et al.*,

2022; Bolan *et al.*, 2023) [8, 2].

Table 1: Effect of tillage and nutrient management practices on plant height, leaf area index (LAI) and dry matter production of *kharif* maize

Treatments	Plant height at harvest (cm)	LAI	Dry matter production (g plant ⁻¹)
Main plots- Tillage practices			
PB + Crop residue	197.92	2.73	282.59
ZT + Crop residue	188.83	2.52	252.80
CT	163.23	2.35	220.87
SEd±	9.22	0.10	12.57
LSD (p=0.05)	25.62	0.28	34.92
Sub Plot- Nutrient management			
100% RDF	191.04	2.53	253.63
Biochar @ 2 t ha ⁻¹	141.67	1.75	201.26
100% RDF + Biochar @ 2 t ha ⁻¹	202.14	3.09	291.79
75% RDF + Biochar @ 2 t ha ⁻¹	198.46	2.80	261.67
SEd±	7.77	0.12	9.16
LSD (p=0.05)	16.33	0.25	19.24
Interaction			
SEd±	13.46	0.21	15.86
LSD (p=0.05)	NS	NS	NS

Effect of tillage and nutrient management on grain and stover yield of *kharif* maize

Grain and stover yield of *kharif* maize were significantly influenced by tillage and nutrient management practices (Table 2). Among tillage practices, permanent bed (PB) recorded significantly higher grain yield (6477 kg ha⁻¹) and stover yield (8638 kg ha⁻¹), followed by zero tillage (ZT) (6038 and 8447 kg ha⁻¹, respectively), whereas conventional tillage (CT) resulted in the lowest yields (5065 and 6790 kg ha⁻¹, respectively). The superior performance under conservation tillage may be attributed to improved soil moisture availability during critical growth stages and reduced surface runoff, which minimized crop stress and facilitated efficient grain filling. In addition, reduced soil disturbance under permanent beds likely preserved soil macropore continuity, enhancing root proliferation and access to water and nutrients during the reproductive phase. These findings corroborate earlier reports of higher maize productivity under conservation tillage across diverse agro- climatic conditions (Busari *et al.*, 2023; Razzaq *et al.*, 2022) [3, 19].

Nutrient management treatments also exerted a significant influence on yield. The treatment 100% RDF + biochar @ 2 t ha⁻¹ recorded the highest grain yield (7383 kg ha⁻¹) and stover yield (9682 kg ha⁻¹), followed by 75% RDF + biochar @ 2 t ha⁻¹ (6354 and 8630 kg ha⁻¹, respectively), while biochar alone resulted in the lowest yields (4574 and 6315 kg ha⁻¹), and 100% RDF alone showed intermediate performance (5128 and 7206 kg ha⁻¹). The enhanced yield under combined application may be attributed to the synergistic interaction between mineral fertilizers and biochar, which ensured sustained nutrient release during grain filling, improved sink capacity and enhanced harvest index. The comparable performance of reduced RDF (75%) with biochar further suggests the potential of biochar to partially substitute mineral fertilizers without significant yield penalty, highlighting its role in sustainable nutrient management. These results are in agreement with Adekiya *et al.* (2023) [1] and Haider *et al.* (2022) [8], who reported significant improvements in maize yield under integrated biochar and fertilizer application. The higher stover yield observed under permanent bed systems may be linked to sustained nutrient uptake, improved canopy development and enhanced soil moisture conservation, which collectively supported greater biomass accumulation. Similarly, biochar- amended treatments likely improved soil moisture

retention and nutrient availability, prolonging active crop growth and promoting vegetative biomass production. The relatively lower stover yield under sole RDF further emphasizes the additional benefits of biochar in improving overall crop productivity. These observations are consistent with previous findings reporting increased above-ground biomass and stover yield under conservation tillage and biochar-based nutrient management systems (Singh *et al.*, 2023; Kumar *et al.*, 2022; Bolan *et al.*, 2023; Jiang *et al.*, 2022) [21, 13 2, 11]. The interaction between tillage and nutrient management was non-significant for both grain and stover yield.

Table 2: Effect of tillage and nutrient management practices on grain and stover yield of *kharif* maize (kg ha⁻¹)

Treatments	Grain yield (kg ha ⁻¹)	Stover yield (kg ha ⁻¹)
Main plots- Tillage practices		
PB + Crop residue	6477	8638
ZT + Crop residue	6038	8447
CT	5065	6790
SEd±	141	298
LSD (p=0.05)	391	829
Sub Plot- Nutrient management		
100% RDF	5128	7206
Biochar @ 2 t ha ⁻¹	4574	6315
100% RDF + Biochar @ 2 t ha ⁻¹	7383	9682
75% RDF + Biochar @ 2 t ha ⁻¹	6354	8630
SEd±	299	497
LSD (p=0.05)	627	1045
Interaction		
SEd±	517	862
LSD (p=0.05)	NS	NS

Conclusion

The results of the present study demonstrate that tillage and nutrient management practices significantly influenced the growth and productivity of *kharif* maize under semi-arid conditions. Among tillage practices, permanent bed planting consistently recorded higher growth parameters, grain yield and stover yield compared to zero and conventional tillage. Similarly, nutrient management treatments showed a clear advantage of combined application, with 100% RDF + biochar @ 2 t ha⁻¹ producing the highest values for growth and yield

attributes. The performance of 75% RDF + biochar was comparable to 100% RDF, indicating the potential for reducing fertilizer inputs without significant yield penalty. Overall, the results suggest that the integration of conservation tillage practices, particularly permanent bed planting, with biochar-based nutrient management is an effective approach for improving maize productivity under the given experimental conditions.

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