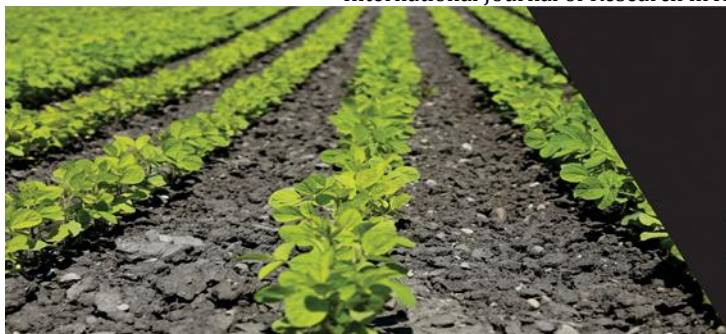




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Impact of maize residue management and nutrient strategies on productivity, profitability and soil fertility of a maize-sunflower cropping system

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Abstract

Crop residue management is a key component of sustainable agriculture and conservation farming, particularly in intensive cropping systems where residue generation is substantial. Maize cultivation generates large quantities of crop residues that are often disposed of through burning, resulting in nutrient losses, environmental pollution and deterioration of soil health. A field experiment was conducted during kharif 2024 and rabi 2024-25 to evaluate the influence of different maize residue management and nutrient strategies on productivity, profitability and soil fertility in a maize sunflower cropping system. The experiment comprised ten treatments involving residue burning, residue incorporation, residue removal, residue mulching under zero tillage, microbial consortium application and varying fertilizer levels. The experiment was laid out in a randomized block design with three replications. Results revealed that maize grain yield ranged from 5775 to 6461 kg ha⁻¹, whereas sunflower seed yield varied from 1069 to 1413 kg ha⁻¹. Residue incorporation with 125% RDF produced the highest maize grain yield (6461 kg ha⁻¹), while residue mulch combined with zero till sowing and recommended fertilizer dose (T₉) recorded the highest sunflower seed yield (1413 kg ha⁻¹), maize equivalent yield (11028 kg ha⁻¹), net returns (Rs.1,24,482 ha⁻¹) and benefit-cost ratio (2.02). Soil fertility was also improved under residue retention treatments, with T₃ recording the highest available nitrogen (154 kg ha⁻¹) and potassium (367 kg ha⁻¹), while T₅ recorded the highest available phosphorus (35.4 kg ha⁻¹). Residue retention and conservation agriculture practices consistently outperformed residue burning and residue removal treatments. The study demonstrates that residue mulching under zero tillage and residue incorporation with adequate nutrient supplementation are effective strategies for improving crop productivity, profitability and long-term soil health in maize sunflower cropping systems.

Keywords: Conservation agriculture, crop residue management, maize equivalent yield, residue mulching, soil fertility, sunflower, zero tillage

Introduction

Maize (*Zea mays L.*) is one of the most important cereal crops globally and serves as a major source of food, feed and industrial raw material. In India, maize cultivation has expanded rapidly due to increasing demand from poultry, starch and biofuel industries. The crop produces large quantities of biomass and generates substantial crop residues after harvest. Sunflower (*Helianthus annuus L.*), an important oilseed crop, is widely cultivated because of its adaptability to diverse agro-climatic conditions, short duration and high-quality edible oil. The maize sunflower cropping system has gained importance in semi-arid regions owing to its higher productivity, efficient resource utilization and economic viability.

Sustainable crop production in intensive cropping systems depends largely on efficient management of crop residues. Crop residues are important sources of organic carbon and plant nutrients, contributing significantly to soil fertility and ecosystem functioning. Gupta *et al.* (2015) [5] reported that nearly one-fourth of nitrogen and phosphorus and more than 70% of potassium absorbed by cereal crops remain in crop residues after harvest, highlighting their potential for nutrient recycling and improved nutrient-use efficiency.

Despite these benefits, residue burning remains a common practice due to labour shortages, mechanization constraints and the need for rapid field preparation. Crop residue burning results in substantial losses of nutrients and organic carbon, reduces microbial activity and contributes to environmental pollution through the emission of greenhouse gases and particulate matter. Bhuvaneshwari *et al.* (2019) [1] reported that residue burning adversely affects soil health by reducing microbial biomass and enzymatic activities, ultimately leading to deterioration of soil fertility and crop productivity.

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Conservation agriculture has emerged as a sustainable alternative to conventional residue disposal practices. Its key principles include minimum soil disturbance, permanent soil cover and diversified crop rotations. Residue retention through mulching improves soil structure, water infiltration, moisture conservation and biological activity while reducing erosion and evaporation losses. Lal (2015) [8] emphasized the role of residue retention in enhancing soil organic carbon sequestration and water-use efficiency. Similarly, Zhao *et al.* (2019) [19] reported increased soil moisture content under residue-retained systems, while Cárceles Rodríguez *et al.* (2022) [2] documented improvements in soil health, nutrient dynamics and crop productivity under conservation agriculture.

Residue incorporation is another effective strategy for crop residue utilization. Through microbial decomposition, incorporated residues gradually release nutrients and improve soil physical and chemical properties. Fu *et al.* (2021) [3] reported that residue incorporation enhances soil aggregation, water-holding capacity and nutrient mineralization. However, residues with wider carbon-to-nitrogen ratios may temporarily immobilize nitrogen during decomposition, necessitating appropriate nutrient management to maximize productivity.

Microbial consortia have gained increasing attention for accelerating residue decomposition and improving nutrient availability. Cellulolytic microorganisms facilitate breakdown of lignocellulosic residues, while phosphate-solubilizing and potassium-mobilizing microorganisms enhance nutrient release and nutrient-use efficiency. Integration of residue management with microbial inoculation and balanced fertilization therefore offers considerable potential for improving productivity and sustaining soil health in maize-based cropping systems.

Recent studies conducted under rice sunflower systems in Telangana have further demonstrated the benefits of residue recycling. Prasad *et al.* (2024) [12] reported that incorporation of rice straw with appropriate nutrient adjustments significantly improved sunflower growth, yield, profitability and resource-use efficiency compared with residue burning and residue removal. Subsequent studies revealed enhanced microbial activity and enzyme dynamics (Prasad *et al.*, 2025a) [11], improved soil moisture conservation and reduced bulk density (Prasad *et al.*, 2025b) [13], and greater aggregate stability and soil organic matter accumulation (Prasad *et al.*, 2025c) [14] under residue retention and incorporation practices. These findings collectively indicate that residue recycling can improve soil quality and crop productivity under semi-arid conditions.

Economic viability is a critical factor influencing adoption of residue management technologies. Conservation agriculture practices often reduce labour and fuel requirements while improving crop productivity and profitability. Naab *et al.* (2017) [9] reported that residue retention significantly enhanced farm income, soil quality and crop productivity compared with conventional systems.

Although substantial information is available on residue management in cereal-based systems, limited research has been conducted on the combined effects of maize residue incorporation, residue mulching, microbial consortium application and varying fertilizer levels in maize sunflower cropping systems under the semi-arid conditions of Telangana.

Therefore, the present investigation was undertaken to evaluate the effect of different maize residue management and nutrient strategies on crop productivity, system profitability and soil fertility, and to identify sustainable residue management practices for maize sunflower cropping systems.

Material and Methods

A field experiment was conducted during kharif 2024 and rabi 2024-25 at Agricultural Research Station Tarnala (18°06'35" North latitude and 78°44'17" East longitude) to evaluate the effect of maize residue management and nutrient strategies on a maize-sunflower cropping system. Experimental soil is sandy clay loam in texture with 66.40% sand, 8.30% silt and 25.30% clay, neutral in soil reaction with pH 7.42, non-saline (EC 0.16 dS m⁻¹), low in organic carbon (0.44%) and available nitrogen (131.3 kg/ha), high in available phosphorus (27.7 kg/ha) and available potassium (302 kg/ha). The study consisted of ten treatments involving residue burning, residue incorporation, residue removal, residue mulching under zero tillage, microbial consortium application and different fertilizer levels.

During Kharif season maize hybrid DHM 206 (100 days duration) was cultivated. Sowing was taken up with pneumatic planter at a spacing of 60 x 20-22cm while during rabi Sunflower hybrid Tilhan SunTech -1 of 95 days duration was grown at a spacing of 45 X 20 cm spacing. The recommended dose of fertilizers for (RDF) for maize is 200-60-50 kg NPK ha⁻¹ with N in 3 equal splits- basal; Knee high stage and tasselling stage; entire P basal & K in two splits 50 % as basal and 50% tasselling stage. For sunflower RDF is 75-90-30 kg NPK ha⁻¹ with N in 3 splits- 50% basal; remaining in 2 splits; P & K basal. All the package of practices outlined by PJTAU were adopted for crop management.

The detailed treatments were T₁ - Maize residue burning + 100% RDF, T₂ - Maize residue incorporation + 100% RDF, T₃ - Maize residue incorporation + 125% RDF, T₄ - Maize residue incorporation + 100% RDF + foliar spray of 19:19:19 at 15 and 30 DAS, T₅ - Maize residue incorporation + microbial consortium spray @ 2% stover + 100% RDF, T₆ - Maize residue incorporation + microbial consortium spray @ 2% stover + 125% RDF, T₇ - Maize residue removal + RDF, T₈ - Maize residue burning + RDF + green manure crop during summer, T₉ - Maize residue mulch + zero till sowing + RDF, T₁₀ - Maize residue mulch + zero till sowing + 125% RDF. The experimental design was RBD with three replications. The biometric observations like plant height (cm) and yield attributes like head diameter (cm), seeds head-1etc., were recorded in each treatment duly tagging the plants and analyzed statistically using ANOVA. Soil analysis was carried by adopting standard procedures as outlined by Jackson (1973) [7]. The data recorded on various parameters during the course of study were statistically analyzed duly following the analysis of variance technique for randomized block design (Panse and Sukhtame, 1985). The statistical significance was tested with 'F' test at 0.05 level of probability and where ever the 'F' value was found significant, critical difference (CD, $p=0.05$) was worked out to test the significance of difference between means.

Table 1: Crop establishment, growth, grain and straw yield of maize during kharif, 2024

Treatment		Plant Population/ha	Pl. Height (cm)	Yield (kg/ha)	
				Grain	Stalk
T ₁	Maize residue burning + 100% RDF	70000	177.7	6293	9773
T ₂	Maize residue incorporation + 100% RDF	70000	172.1	5833	9664
T ₃	Maize residue incorporation + 125% RDF	65000	184.0	6461	9480
T ₄	Maize residue incorporation + 100% RDF+ 2 Foliar sprays (19:19:19) at 15 DAS & 30 DAS	65000	169.5	5833	9957
T ₅	Maize residue incorporation +Microbial consortium spray @ 2%stover + 100% RDF	65000	191.4	6000	9407
T ₆	Maize residue incorporation +Microbial consor spray @ 2%stover + 125% RDF	60000	176.0	6408	9725
T ₇	Maize residue removal + RDF	72500	170.8	6067	9537
T ₈	Maize residue burning + RDF + green manure crop (during summer)	75000	178.2	5775	9710
T ₉	Maize residue mulch + Zero till sowing + RDF	70000	182.0	5975	9577
T ₁₀	Maize residue mulch + Zero till sowing + 125% RDF	65000	174.3	6125	9532
	Mean	70000	177.6	6077	9636
	CD @ 5%			257	NS
	CV (%)			10.93	11.33

Table 2: Crop establishment, growth, seed and stalk yield of sunflower under different maize residue management options

Treatment		Plant Population/ ha	Plant Height		Head Diameter (cm)	No. of Seeds/ Head	Seed Yield (kg/ha)	Stalk Yield (kg/ha)
			At Veg stage (cm)	At harvest (cm)				
T ₁	Maize residue burning + 100% RDF	99167	78.0	144.9	9.7	537.2	1094	1742
T ₂	Maize residue incorporation (shredder+ rotavator) + 100% RDF	99167	79.5	152.0	10.2	585.5	1120	1883
T ₃	Maize residue incorporation + 125% RDF	98333	81.2	144.8	10.6	547.9	1163	1708
T ₄	Maize residue incorporation + 100% RDF+ 2 Foliar sprays (19:19:19) at 15 DAS & 30 DAS	96667	79.0	152.6	10.2	561.8	1092	1692
T ₅	Maize residue incorporation +Microbial consortium spray@ 2%stover + 100% RDF	99167	76.8	146.2	10.5	602.9	1154	1696
T ₆	Maize residue incorporation +Microbial consortium spray @ 2%stover + 125% RDF	98333	77.4	148.4	10.1	556.0	1112	1608
T ₇	Maize residue removal + RDF	99167	83.2	144.6	8.9	553.0	1233	1612
T ₈	Maize residue burning + RDF + green manure crop (during summer)	100000	82.7	140.6	9.0	582.9	1069	1698
T ₉	Maize residue mulch + Zero till sowing + RDF	98333	82.5	135.3	10.9	675.7	1413	1588
T ₁₀	Maize residue mulch + Zero till sowing + 125% RDF	98333	92.9	147.8	10.4	652.9	1360	1731
	SE(m)±		6.63	7.15	0.36	28.74	59.89	74.21
	CD @ 5%		NS	NS	1.08	85.40	179.32	NS
	CV %		14.113	8.50	6.28	8.50	8.78	7.58

Table 3: System Productivity and Profitability of maize-sunflower cropping system under different maize residue management options

Treatment			Productivity (kg ha ⁻¹)						System Profitability			
		Kharif maize				Rabi Sunflower		System Maize Eq Yield	Cost of Cultivation	Gross returns	Net Returns	B:C ratio
	Grain	Straw	MGEY of straw	MGEY (G + S)	Seed	Maize Eq Yield of Sunflower						
T ₁	Maize residue burning + 100% RDF	6293	9773	440	6733	1094	3580	10313	125610	223168	97558	1.78
T ₂	Maize residue incorporation (shredder+ rotavator) + 100% RDF	5833	9664	435	6268	1120	3665	9933	127110	225048	97938	1.77
T ₃	Maize residue incorporation + 125% RDF	6461	9480	427	6888	1163	3804	10692	129761	228142	98381	1.76
T ₄	Maize residue incorporation + 100% RDF+ 2 Foliar sprays (19:19:19) at 15 DAS & 30 DAS	5833	9957	449	6282	1092	3572	9854	127485	222986	95501	1.75
T ₅	Maize residue incorporation +Microbial consortium spray@ 2%stover + 100% RDF	6000	9407	424	6424	1154	3776	10200	128735	227536	98801	1.77
T ₆	Maize residue incorporation +Microbial consortium spray @ 2% stover + 125% RDF	6408	9725	438	6846	1112	3637	10483	131386	224442	93055	1.71
T ₇	Maize residue removal + RDF	6067	9537	430	6497	1233	4033	10530	125610	233238	107628	1.86
T ₈	Maize residue burning + RDF + green manure crop (during summer)	5775	9710	437	6212	1069	3498	9710	128110	221348	93238	1.73
T ₉	Maize residue mulch + Zero till sowing + RDF	5975	9577	431	6406	1413	4622	11028	121860	246342	124482	2.02
T ₁₀	Maize residue mulch + Zero till sowing + 125% RDF	6125	9532	429	6554	1360	4450	11004	124511	242520	118009	1.95

MGEY Maize Grain Equivalent Yield, Sale price: Maize Grain: Rs 22. 25/kg; Straw: Rs 1.00//kg Sunflower - Rs 72. 80/kg

Table 4: Soil fertility changes after harvest of sunflower under different maize residue management options

	Treatments	pH	EC (dSm ⁻¹)	Avail N (kg ha ⁻¹)	Avail P (kg ha ⁻¹)	Avail K (kg ha ⁻¹)
	Initial	7.42	0.16	131.2	27.7	302
	After Maize	7.62	0.21	152.2	29.7	294
T ₁	Maize residue burning + 100% RDF	7.26	0.15	134.9	29.4	273
T ₂	Maize residue incorporation (shredder+ rotavator) + 100% RDF	7.50	0.14	142.4	30.5	305
T ₃	Maize residue incorporation + 125% RDF	7.45	0.17	154.0	34.7	367
T ₄	Maize residue incorporation + 100% RDF+ 2 Foliar sprays (19:19:19) at 15 DAS & 30 DAS	7.61	0.14	142.4	29.8	327
T ₅	Maize residue incorporation +Microbial consortium spray@ 2%stover + 100% RDF	7.54	0.15	149.9	35.4	332
T ₆	Maize residue incorporation +Microbial consortium spray @ 2%stover + 125% RDF	7.21	0.17	146.2	30.3	340
T ₇	Maize residue removal + RDF	7.33	0.17	138.7	35.0	300
T ₈	Maize residue burning + RDF + green manure crop (during summer)	7.42	0.15	134.9	32.2	309
T ₉	Maize residue mulch + Zero till sowing + RDF	7.60	0.14	131.2	29.8	332
T ₁₀	Maize residue mulch + Zero till sowing + 125% RDF	7.52	0.16	134.9	31.7	318
	SE(m)±	0.14	0.02	3.99	2.85	20.85
	CD @ 5%	NS	NS	11.85	5.50	61.95
	CV %	3.11	7.49	8.59	15.48	11.27

Results and Discussion

Effect of Residue Management Practices on Growth and Yield of Maize

Crop establishment and growth of maize were not significantly influenced by residue management practices, as evidenced by the non-significant differences in plant population and plant height (Table 1). However, numerical variations were observed among treatments. Plant height ranged from 169.5 to 191.4 cm, with the highest value recorded under residue incorporation coupled with microbial consortium application and 100% RDF (T₅). The improved vegetative growth under microbial inoculation may be attributed to accelerated decomposition of crop residues and enhanced nutrient mineralization. Cellulolytic microorganisms facilitate the breakdown of lignocellulosic materials and improve nutrient availability, particularly nitrogen and phosphorus, thereby promoting plant growth and biomass accumulation. Residue incorporation enhances nutrient recycling, soil aggregation, microbial activity and water infiltration, leading to improved nutrient uptake and crop productivity. Similar benefits of residue incorporation and conservation agriculture practices have been reported by Gathala *et al.* (2015) [4], Naab *et al.* (2017) [9] and Sarkar *et al.* (2020) [16].

Under Telangana conditions, Prasad *et al.* (2024) [12] reported significantly greater dry matter production and productivity under residue incorporation treatments compared with residue burning, while Prasad *et al.* (2025c) [14] observed improvements in soil aggregation and soil organic matter accumulation under residue-retained systems. Enhanced aggregate stability improves soil structure, root proliferation and nutrient retention, which may partly explain the higher maize productivity observed in the present study.

Residue burning treatments (T₁ and T₈) recorded comparatively lower grain yields. Burning of crop residues causes losses of nitrogen, sulphur and organic carbon and adversely affects soil biological activity. Gupta *et al.* (2015) [5] and Bhuvaneshwari *et al.* (2019) [1] reported that residue burning reduces nutrient availability and microbial activity, resulting in lower crop productivity. Similar observations were made by Prasad *et al.* (2025a) [11], who reported significantly lower microbial populations and enzyme activities under residue burning

compared with residue incorporation and residue retention treatments.

Although zero tillage with residue mulch (T₉ and T₁₀) did not produce the highest maize grain yield, yields remained comparable to residue incorporation treatments, indicating that conservation agriculture practices can sustain productivity while minimizing soil disturbance and reducing cultivation costs.

Residual Effect of Maize Residue Management on Growth and Yield of Sunflower

The residual effects of residue management were more pronounced in sunflower than in maize. Plant population was not significantly affected by treatments, indicating that residue management had little influence on crop establishment. However, significant differences were observed in head diameter, number of seeds per head and seed yield (Table 2).

The highest head diameter (10.9 cm) and number of seeds per head (675.7) were recorded under residue mulch with zero till sowing and RDF (T₉). The improved reproductive growth under residue mulch may be attributed to enhanced soil moisture conservation, improved nutrient availability and favourable soil physical conditions during flowering and seed filling stages.

Sunflower seed yield ranged from 1069 to 1413 kg ha⁻¹. The highest seed yield was recorded under T₉ (1413 kg ha⁻¹), followed by T₁₀ (1360 kg ha⁻¹). Compared with residue burning (T₁), T₉ increased sunflower seed yield by nearly 29 per cent. The superior performance of residue mulch treatments may be attributed to reduced soil evaporation, greater soil water storage, enhanced microbial activity and improved nutrient cycling. Zhao *et al.* (2019) [19] reported that residue retention increased soil moisture content and improved crop productivity, while

Cárceles Rodríguez *et al.* (2022) [2] documented improvements in soil health and crop performance under conservation agriculture systems.

The results are further supported by Prasad *et al.* (2025b) [13], who observed significantly higher soil moisture content and lower bulk density under residue-retained treatments in a rice sunflower system. Improved moisture availability during critical growth stages likely enhanced seed setting and seed filling. Similarly, Prasad *et al.* (2024) [12] reported significantly

higher sunflower yield, yield attributes and profitability under residue incorporation and residue-retained treatments compared with residue burning and residue removal. These findings indicate that residue recycling creates favourable soil conditions that support higher productivity of succeeding crops.

Among residue incorporation treatments, T₅ recorded relatively higher sunflower yield than T₂, T₄ and T₆, indicating the beneficial role of microbial consortium application. Enhanced decomposition and nutrient mineralization under microbial inoculation may have improved nutrient availability during crop growth. Similar responses were reported by Fu *et al.* (2021) [3] and Prasad *et al.* (2025a) [11], who observed enhanced microbial activity and nutrient-transforming enzyme activities under residue incorporation treatments.

System Productivity

System productivity expressed as maize grain equivalent yield (MGEY) provided a comprehensive assessment of treatment performance across the maize sunflower sequence. Significant variation was observed among treatments (Table 3). The highest MEY (11028 kg ha⁻¹) was recorded under residue mulch with zero tillage and RDF (T₉), followed by T₁₀ (11004 kg ha⁻¹). Compared with residue burning, residue mulching increased system productivity by approximately 10.3%.

The superiority of residue mulch treatments may be attributed to cumulative improvements in soil moisture conservation, nutrient cycling and soil biological activity across both crops. Surface residues reduce runoff and evaporation losses while increasing infiltration and water availability within the root zone. Similar improvements in productivity under conservation agriculture have been reported by Rusinamhodzi *et al.* (2011) [15], Naab *et al.* (2017) [9] and Sarker *et al.* (2022) [17].

Regional studies also support the present findings. Prasad *et al.* (2024) [12] reported significant improvements in productivity and profitability under residue retention and residue incorporation compared with residue burning. Furthermore, Prasad *et al.* (2025c) [14] demonstrated enhanced aggregate stability and soil organic matter accumulation under residue-retained systems, indicating long-term benefits for system sustainability.

Economic Analysis

Economic analysis (Table 3) indicated clear advantages of residue retention over residue burning. The highest net returns (Rs.124,482 ha⁻¹) and benefit-cost ratio (2.02) were recorded under T₉, followed by T₁₀ (Rs.118,009 ha⁻¹ and 1.95, respectively).

The greater profitability under residue mulch treatments resulted from higher sunflower productivity coupled with reduced tillage costs. Zero tillage reduces expenditure on land preparation, labour and fuel while maintaining crop productivity. Similar economic benefits of conservation agriculture have been reported by Naab *et al.* (2017) [9] and Gathala *et al.* (2015) [4].

The present findings are also consistent with those of Prasad *et al.* (2024) [12], who reported significantly higher gross returns, net returns and benefit-cost ratios under residue incorporation and residue-retained treatments compared with residue burning. The improved profitability observed under residue-retained systems therefore reflects both enhanced productivity and reduced production costs.

Effect on Soil Fertility and Nutrient Dynamics

Post-harvest soil analysis revealed significant improvements in soil fertility under residue incorporation and residue retention treatments. Soil pH and EC remained within acceptable limits across treatments, indicating that residue management practices did not adversely affect soil chemical properties.

Available nitrogen was highest under residue incorporation with 125% RDF (T₃), recording 154 kg ha⁻¹. The increase in available nitrogen may be attributed to mineralization of incorporated residues and enhanced microbial activity. Similar improvements in nitrogen availability under residue incorporation have been reported by Sarkar *et al.* (2020) [16].

Available phosphorus was highest under T₅ (35.4 kg ha⁻¹), indicating the beneficial effect of microbial consortium application. Microorganisms associated with residue decomposition produce organic acids and *phosphatase* enzymes that solubilize native soil phosphorus and enhance its availability. Similar observations were reported by Fu *et al.* (2021) [3].

The highest available potassium content (367 kg ha⁻¹) was recorded under T₃. Crop residues contain substantial quantities of potassium that are readily released during decomposition. Enhanced potassium recycling under residue-retained systems has also been reported by Singh *et al.* (2018) [18].

The higher nutrient status observed under residue incorporation and residue retention may also be linked to improvements in soil biological activity and aggregation. Prasad *et al.* (2025a) [11] reported significantly higher microbial populations and greater *urease*, *dehydrogenase*, *phosphatase* and *β-glucosidase* activities under residue incorporation and retention treatments. Likewise, Prasad *et al.* (2025c) [14] reported higher aggregate stability, mean weight diameter and soil organic matter content under residue-retained systems. Improved aggregation protects organic matter and enhances nutrient retention, thereby contributing to long-term soil fertility and sustainability.

Implications for Sustainable Agriculture

The present findings demonstrate that conservation agriculture-based residue management practices are superior to residue burning in terms of productivity, profitability and soil fertility. Residue mulch under zero tillage improved sunflower productivity, system productivity and economic returns, while residue incorporation enhanced nutrient availability and soil fertility.

The results corroborate global evidence reported by Hobbs *et al.* (2008) [6], Lal (2015) [8], Sarkar *et al.* (2020) [16] and Sarker *et al.* (2022) [17], as well as regional studies conducted in Telangana by Prasad *et al.* (2024, 2025a, 2025b and 2025c). Collectively, these studies demonstrate that residue recycling improves soil moisture conservation, microbial activity, aggregate stability, nutrient cycling and crop productivity. Therefore, integration of residue retention, microbial inoculation and balanced fertilization offers a viable strategy for sustainable intensification of maize sunflower cropping systems under semi-arid conditions.

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