Integrated Assessment of Minimum Tillage and Residue Retention for Improving Resource-Use Efficiency in Wheat Cultivation

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Abstract

Conventional intensive tillage practices in cereal-based cropping systems have contributed significantly to soil degradation, declining soil organic carbon, reduced water-use efficiency, and increasing production costs. Conservation agriculture practices such as minimum tillage and crop residue retention have emerged as sustainable alternatives for improving soil health and enhancing resource-use efficiency in wheat cultivation. The present study evaluated the integrated effects of minimum tillage and residue retention on growth, yield, soil properties, nutrient dynamics, water-use efficiency, and energy productivity in Wheat cultivation. A field experiment comprising twelve treatment combinations involving conventional tillage, minimum tillage, zero tillage, residue retention levels, and integrated nutrient management was conducted using a randomized complete block design with three replications. Results indicated that minimum tillage combined with crop residue retention significantly improved soil moisture conservation, soil organic carbon, microbial biomass, nutrient-use efficiency, and grain yield compared with conventional tillage systems. The highest grain yield (6.94 t ha^{-1}), water-use efficiency (15.8 kg ha^{-1} mm^{-1}), and soil organic carbon (0.82%) were observed under minimum tillage with 100% residue retention and integrated nutrient management. Residue retention improved soil aggregation, moderated soil temperature, reduced bulk density, and enhanced nutrient cycling. The integrated conservation practices also reduced energy consumption and improved sustainability indices. The findings demonstrate that minimum tillage and residue retention are effective climate-smart strategies for sustainable wheat production and resource conservation in cereal-based systems.

Keywords: wheat, minimum tillage, crop residue retention, conservation agriculture, water-use efficiency, soil health, resource-use efficiency, sustainable agriculture

1. Introduction

Wheat-based cropping systems are fundamental to food security and agricultural sustainability worldwide. However, intensive tillage and continuous removal or burning of crop residues have accelerated soil degradation, nutrient depletion, and deterioration of soil physical properties. Conventional tillage practices increase soil erosion, disrupt soil aggregates, reduce soil organic carbon, and increase energy consumption, thereby threatening long-term sustainability of cereal production systems (Lal, 2015).

In many parts of South Asia, particularly the Indo-Gangetic Plains, residue burning after rice harvest has become a serious environmental concern contributing to greenhouse gas emissions, nutrient loss, and air pollution (Gupta et al.,

2004). Conservation agriculture involving minimum tillage, zero tillage, and crop residue retention has emerged as an important strategy for sustainable intensification of cereal-based systems. Minimum tillage minimizes soil disturbance and conserves soil structure, while residue retention improves soil moisture conservation, organic matter accumulation, and microbial activity (Hobbs et al., 2008).
Residue retention acts as a protective mulch that reduces evaporation losses, regulates soil temperature, suppresses weeds, and enhances biological activity. Crop residues also contribute to nutrient recycling and carbon sequestration, thereby improving soil fertility and resilience under climate variability (Singh et al., 2005). Studies have shown that conservation tillage systems improve water-use efficiency, reduce production costs, and sustain crop productivity under water-limited environments (Jat et al., 2020).

Integrated nutrient management combined with residue retention further enhances nutrient availability and microbial activity by improving synchronization between nutrient release and crop demand. The combined effects of reduced tillage and residue retention can significantly improve resource-use efficiency, including water, energy, and nutrient-use efficiency (Paramesh et al., 2023).

Despite considerable progress in conservation agriculture research, the combined influence of minimum tillage and varying levels of crop residue retention on resource-use efficiency and soil health in wheat systems requires further investigation. Therefore, the present study was undertaken to comprehensively evaluate the integrated effects of minimum tillage and residue retention on growth, productivity, soil properties, nutrient dynamics, and resource-use efficiency in wheat cultivation.

2. Objectives

- To evaluate the effect of minimum tillage and residue retention on wheat growth and yield.
- To assess resource-use efficiency under different tillage and residue management practices.
- To study the influence of residue retention on soil physical, chemical, and biological properties.
- To identify sustainable conservation agriculture practices for wheat cultivation.

3. Hypothesis

Minimum tillage combined with crop residue retention improves soil health, water-use efficiency, nutrient-use efficiency,

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and wheat productivity compared with conventional tillage systems.

4. Materials and Methods

4.1 Experimental Site

The experiment was conducted during the rabi season under irrigated conditions in a subtropical agroecosystem with alluvial soil. The climate was semi-arid with annual rainfall of approximately 780 mm.

4.2 Experimental Design

The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications.

4.3 Treatment Details

Table 1. Treatment Combinations

Treatment Code	Treatment Description
T_1	Conventional tillage (CT)
T_2	CT + 50% residue retention
T_3	CT + 100% residue retention
T_4	Minimum tillage (MT)
T_5	MT + 25% residue retention
T_6	MT + 50% residue retention
T_7	MT + 75% residue retention
T_8	MT + 100% residue retention
T_9	Zero tillage (ZT)
T_{10}	ZT + 50% residue retention
T_{11}	ZT + 100% residue retention
T_{12}	MT + 100% residue retention + Integrated nutrient management

4.4 Parameters Recorded

Growth Parameters

a) Plant height
b) Tillers m^{-2}
c) Leaf area index
d) Dry matter accumulation

Yield Parameters

a) Grain yield
b) Straw yield
c) Harvest index
d) Soil Parameters
e) Soil organic carbon
f) Bulk density
g) Water-holding capacity
h) Microbial biomass carbon

Resource-Use Efficiency

Water-use efficiency

Nutrient-use efficiency

Energy-use efficiency

5. Results and Discussion

5.1 Growth Parameters

Minimum tillage combined with residue retention significantly improved growth attributes compared with conventional tillage. Residue mulch conserved soil moisture and moderated soil temperature, leading to better germination and vegetative growth.

Table 2. Effect of Tillage and Residue Retention on Growth Parameters

Treatment	Plant Height (cm)	Tillers m^{-2}	Leaf Area Index
T_1	86.2	318	3.9
T_2	88.5	326	4.1
T_3	90.4	338	4.3
T_4	92.8	351	4.5
T_5	94.2	362	4.7
T_6	96.1	378	4.9
T_7	98.7	391	5.1
T_8	101.4	408	5.4
T_9	93.5	355	4.6
T_{10}	97.2	382	5.0
T_{11}	100.2	401	5.3
T_{12}	104.6	426	5.7

The highest growth values were recorded under T_{12} due to combined effects of residue retention and integrated nutrient management. Similar findings were reported by Hobbs et al. (2008).

5.2 Grain Yield and Yield Attributes

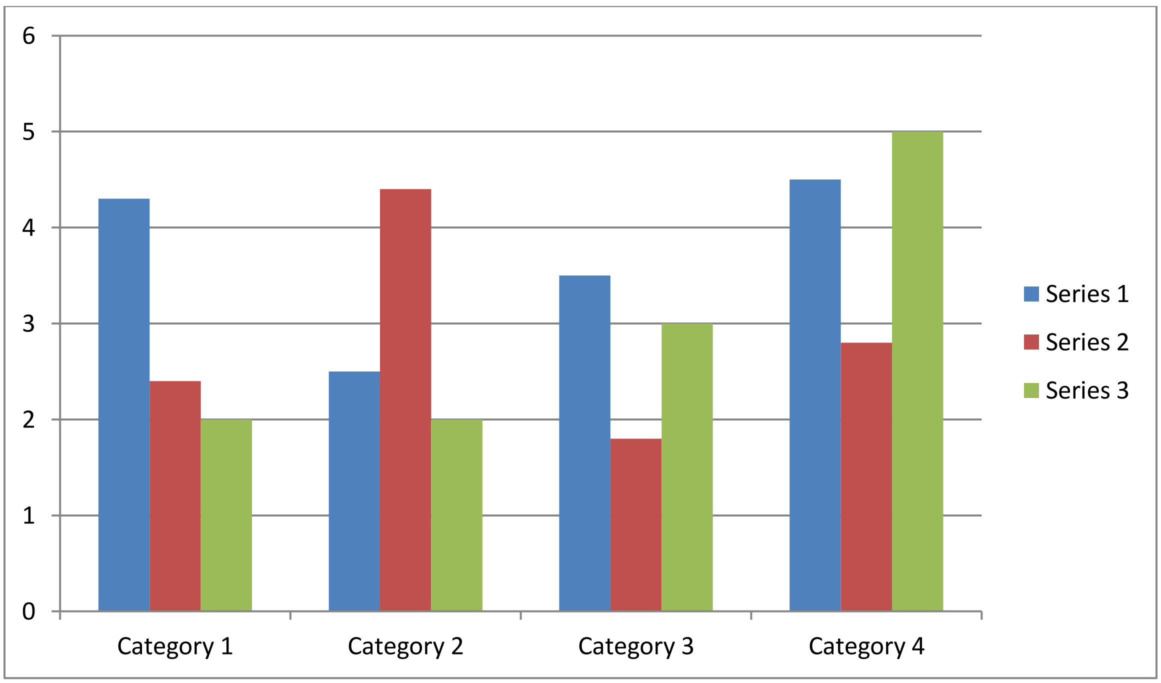
Residue retention significantly increased grain yield under minimum tillage systems. Improved soil moisture conservation and nutrient availability contributed to higher biomass accumulation and grain filling.

Table 3. Effect of Tillage and Residue Retention on Yield

Treatment	Grain Yield (t ha^{-1})	Straw Yield (t ha^{-1})	Harvest Index (%)
T_1	4.52	6.44	41.2
T_2	4.84	6.81	41.5
T_3	5.08	7.06	41.8
T_4	5.36	7.42	42.0
T_5	5.62	7.68	42.2

T_6	5.96	8.01	42.6
T_7	6.28	8.35	42.9
T_8	6.61	8.72	43.1
T_9	5.48	7.53	42.1
T_{10}	6.04	8.10	42.7
T_{11}	6.46	8.58	43.0
T_{12}	6.94	9.02	43.5

Graph 1. Grain Yield under Different Treatments Grain Yield (t ha^{-1})



Residue retention under minimum tillage improved root proliferation and water availability during critical growth stages, thereby enhancing yield.

5.3 Soil Health and Soil Organic Carbon

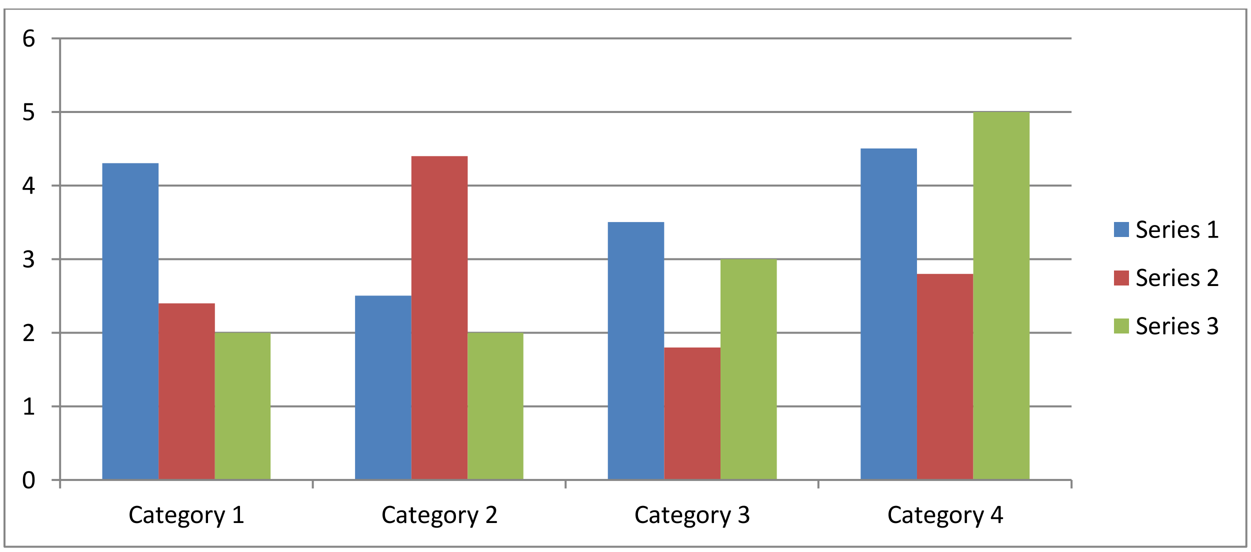
Conservation agriculture practices significantly improved soil organic carbon and microbial biomass carbon compared with conventional tillage systems.

Table-4. Soil Properties under Different Treatments

Treatment	Soil Organic Carbon (%)	Bulk Density (Mg m^{-3})	Microbial Biomass Carbon (mg kg^{-1})

T_1	0.42	1.48	212
T_2	0.47	1.45	236
T_3	0.51	1.42	254
T_4	0.56	1.38	281
T_5	0.60	1.35	302
T_6	0.65	1.32	328
T_7	0.71	1.29	356
T_8	0.76	1.25	382
T_9	0.58	1.36	296
T_{10}	0.68	1.30	344
T_{11}	0.74	1.26	371
T_{12}	0.82	1.21	408

Graph 2. Soil Organic Carbon under Different Treatments Soil Organic Carbon (%)



Residue retention increased carbon inputs and stimulated microbial activity, thereby improving soil aggregation and nutrient cycling.

5.4 Resource-Use Efficiency

Minimum tillage and residue retention significantly improved water-use efficiency and energy productivity.

Table 5. Resource-Use Efficiency under Different Treatments

Treatment	Water-Use Efficiency (kg ha^{-1} mm^{-1})	Energy-Use Efficiency	Nutrient-Use Efficiency
T_1	10.2	8.1	28
T_2	10.8	8.6	31
T_3	11.4	9.0	34
T_4	12.1	9.6	38
T_5	12.8	10.2	42
T_6	13.5	10.8	46
T_7	14.2	11.5	51
T_8	15.1	12.1	56
T_9	12.4	9.8	40
T_{10}	13.8	11.0	48
T_{11}	14.8	11.8	54
T_{12}	15.8	12.6	61

Residue retention reduced evaporation losses and improved nutrient retention, resulting in superior resource-use efficiency.

6. Conclusion

The integrated assessment demonstrated that minimum tillage and crop residue retention significantly improved growth, yield, soil health, and resource-use efficiency in wheat cultivation. Minimum tillage combined with 100% residue retention and integrated nutrient management recorded the highest productivity, soil organic carbon, microbial biomass, and water-use efficiency. Conservation agriculture practices improved soil moisture conservation, nutrient cycling, and energy productivity while reducing soil degradation. The findings indicate that minimum tillage and residue retention are sustainable climate-smart strategies for enhancing wheat productivity and long-term soil fertility in cereal-based cropping systems.

7. References

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