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Artificial Intelligence–Driven Assessment of Conservation Agriculture Practices on Crop Water Productivity, Grain Quality and Soil Health of Wheat in Typic Ustochrept Soils of Western U. P.

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Abstract

A decade-long field investigation (2015–2025) was conducted across 80 farmers' fields in Meerut, Ghaziabad, Hapur, Bulandshahr, and Muzaffarnagar districts of western Uttar Pradesh to evaluate the impact of conservation agriculture (CA) practices on crop productivity, water use efficiency, soil health, grain quality, and environmental sustainability in wheat grown on ustochrept soils. The experiment was laid out in a randomized block design with five treatments: conventional tillage (T_1), zero tillage without residue (T_2), zero tillage with residue retention (T_3), and furrow irrigated raised beds without residue (T_4), and furrow irrigated raised beds with residue retention (T_5).

Results revealed a consistent improvement in crop productivity and resource-use efficiency under conservation practices. Grain yield increased from 4.45–4.85 t ha⁻¹ in 2015 to 4.58–5.72 t ha⁻¹ in 2025, with the highest yield recorded under T_5 . Water productivity improved significantly from 1.20 to 2.15 kg m⁻³, while irrigation water use decreased from 520 mm in conventional practice to 395 mm under T_5 , indicating enhanced water-use efficiency.

Soil health parameters showed substantial improvement over time, with soil organic carbon increasing from 0.38–0.48% in 2015 to 0.41–0.68% in 2025. Labile and particulate organic carbon fractions also increased significantly under residue-retained treatments. Microbial biomass carbon rose from 180 to 330 mg kg⁻¹, accompanied by higher enzymatic activities, reflecting improved biological functioning of soil. Bulk density decreased from 1.58 to 1.38 Mg m⁻³, while infiltration rate increased from 1.5 to 3.6 cm hr⁻¹, indicating better soil structure and porosity.

Grain quality parameters such as protein content improved from 11.2% to 13.8%, and nutrient uptake increased significantly, with nitrogen uptake reaching up to 140 kg ha⁻¹ under conservation treatments. Economic returns were also higher, with net returns increasing up to Rs. 99,000 ha⁻¹ and benefit-cost ratio reaching 2.94 under T_5 .

Energy use efficiency increased from 5.0 to 8.03, while carbon footprint decreased from 750 to 480 kg CO₂-eq t⁻¹ grain, demonstrating environmental sustainability. Artificial intelligence models showed improved prediction accuracy with R^2 up to 0.95. However, conservation agriculture practices, particularly residue retention with raised bed planting, significantly enhanced productivity, profitability, soil health, and climate resilience of wheat systems.

Keywords: Conservation agriculture, wheat productivity, soil health, water productivity, artificial intelligence

Introduction

The rice–wheat production system of the Indo-Gangetic Plains (IGP), particularly in Western Uttar Pradesh, has been a cornerstone of India's food security but is now facing serious sustainability challenges due to intensive input use and conventional tillage practices. Continuous puddling in rice followed by intensive tillage for wheat has resulted in soil structure degradation, declining soil organic carbon (SOC), and inefficient water and nutrient use. Lal (2004) reported that intensive cultivation in alluvial soils leads to SOC depletion rates of 0.3–0.5 Mg C ha⁻¹ year⁻¹, which directly affects soil productivity and resilience. In Western Uttar Pradesh, SOC levels in Typic Ustochrept soils have declined to 0.35–0.45%, significantly below the critical threshold (≈0.75%) required for maintaining soil quality.

Wheat productivity in this region, although relatively high (4.5–5.5 t ha⁻¹), has shown signs of stagnation over the past decade. Conventional tillage requires 4–6 field operations,

increasing fuel consumption by 60–80 L ha⁻¹ and raising the cost of cultivation by Rs. 5,000–7,000 ha⁻¹. Delayed sowing due to prolonged land preparation further reduces yield potential by 1–1.5% per day after the optimum sowing window. In contrast, zero tillage-based systems enable timely sowing and reduce turnaround time between crops by 7–10 days, leading to yield advantages of 8–15% (Jat *et al.*, 2014) [11]. Kumar observed that long-term adoption of conservation-based practices increased system productivity by 12–18% and net returns by 20–30% in the north-western IGP.

Water scarcity is emerging as a major constraint in wheat production systems. The average irrigation requirement for conventionally tilled wheat ranges from 450 to 550 mm, with water productivity values of 1.2–1.4 kg m⁻³. However, inefficient irrigation practices lead to substantial water losses through evaporation and deep percolation. Residue-based conservation systems significantly reduce these losses. Surface residue cover of 5–7 t ha⁻¹ has been shown to reduce soil evaporation by 25–40% and increase soil moisture retention by 15–20%. Humphreys *et al.* (2010) [10] reported irrigation water savings of 15–25% in zero tillage systems, while furrow irrigated raised bed (FIRB) systems achieved savings of up to 30–35%. Consequently, crop water productivity under these systems increased to 1.8–2.2 kg m⁻³, representing a 30–50% improvement over conventional practices.

Soil health degradation is another critical issue in intensively cultivated systems. Continuous tillage disrupts soil aggregates, accelerates organic matter oxidation, and reduces microbial activity. Long-term studies indicate that residue retention and reduced tillage significantly improve soil physical, chemical, and biological properties. SOC levels in CA-based systems have been reported to increase from 0.38–0.44% to 0.55–0.70% over 8–10 years, with annual sequestration rates of 0.4–0.8 Mg C ha⁻¹. Improvements in soil aggregation (20–35%), infiltration rate (25–40%), and water-holding capacity (10–20%) have also been documented. Biological indicators of soil health show substantial enhancement under conservation-based practices. Microbial biomass carbon increases by 25–45%, reflecting improved microbial activity and nutrient cycling. Enzyme activities such as dehydrogenase and phosphatase have been reported to increase by 30–60%, indicating enhanced soil biological functioning. In Typic Ustochrept soils, bulk density typically decreases from 1.52–1.60 Mg m⁻³ under conventional tillage to 1.38–1.45 Mg m⁻³ under CA systems, facilitating better root growth and water movement. Naresh *et al.* (2020, 2023) [19, 21] in Western Uttar Pradesh demonstrated that residue-based zero tillage increased SOC by 0.15–0.22%, improved infiltration rate by 22–34%, and enhanced microbial biomass carbon by 28–40% compared to conventional tillage.

Grain quality is closely linked to soil fertility and water availability. In conventional systems, wheat protein content typically ranges from 10.5 to 11.8%, whereas conservation-based systems have shown improvements up to 12.5–13.8% due to enhanced nitrogen-use efficiency and improved soil moisture conditions. Test weight has been reported to increase from 38–40 g under conventional practices to 41–44 g under residue-retained systems. Gluten content also improves by 2–4 percentage points, contributing to better processing quality. These improvements are attributed to sustained nutrient availability and reduced stress during

grain filling. Moreover, conservation-based practices are their role in reducing greenhouse gas emissions and enhancing climate resilience. Reduced tillage lowers fuel consumption by 50–60%, thereby decreasing carbon dioxide emissions. Residue retention contributes to carbon sequestration, with estimates ranging from 0.4 to 0.8 Mg C ha⁻¹ year⁻¹. Improved soil moisture retention and reduced temperature fluctuations enhance crop tolerance to drought and heat stress, which are becoming increasingly frequent under changing climatic conditions.

Despite these well-documented benefits, the performance of conservation-based systems varies across locations due to spatial variability in soil properties, weather conditions, and management practices. Conventional statistical approaches often fail to capture such complex interactions. Artificial intelligence (AI) and machine learning (ML) techniques provide a robust framework for analyzing large datasets and identifying nonlinear relationships among variables. Bengio *et al.* demonstrated that deep learning models can effectively handle high-dimensional data and improve prediction accuracy in complex systems. In agricultural applications, AI models such as random forest and artificial neural networks have achieved prediction accuracies (R²) ranging from 0.85 to 0.95 for crop yield, soil properties, and water productivity. Integration of remote sensing data with AI further enhances the spatial and temporal evaluation of agricultural systems. Vegetation indices such as normalized difference vegetation index (NDVI) have shown strong correlations ($r = 0.75\text{--}0.90$) with crop biomass and yield. Soil moisture indices derived from satellite data provide additional inputs for improving model predictions. These technologies enable real-time monitoring and large-scale assessment across heterogeneous farmer fields. Therefore, scientifically validated evidence indicates that conservation-based management practices significantly improve crop water productivity, grain quality, and soil health while reducing input use and environmental impacts. The integration of AI-based analytical tools with long-term, farmer-participatory field data provides a comprehensive approach to evaluate these systems under real-world conditions. This study aims to generate robust, data-driven insights into the sustainability and efficiency of wheat production systems in Typic Ustochrept soils of Western Uttar Pradesh, contributing to climate-resilient and resource-efficient agriculture in the Indo-Gangetic Plains.

Materials and Methods

The study was conducted over a ten-year period (2015–2025) in farmers' participatory mode across 100 farmer fields distributed in five districts of Western Uttar Pradesh, namely Meerut, Ghaziabad, Hapur, Bulandshahr, and Muzaffarnagar. The region is characterized by a semi-arid to sub-humid climate with hot summers and cool winters. The mean annual rainfall ranges from 700 to 800 mm, of which about 80% is received during the monsoon season. The soils of the experimental sites were classified as Typic Ustochrepts, with sandy loam to loam texture, slightly alkaline reaction (pH 7.4–8.2), low to medium soil organic carbon (0.38–0.44%), and medium fertility status. The experiment was designed using a randomized block design (RBD) in a farmer-participatory framework, where each farmer's field was considered as one replication. Each farmer allocated a uniform area of approximately 0.1 ha, which was subdivided into five treatment plots. The

treatments consisted of: (T₁) conventional tillage (CT) with residue removal; (T₂) zero tillage without residue retention (ZT-R); (T₃) zero tillage with residue retention (ZT+R) at 5–7 t ha⁻¹; (T₄) furrow irrigated raised beds without residue (FIRB-R); and (T₅) furrow irrigated raised beds with residue retention (FIRB+R).

Wheat was grown during the rabi season each year using regionally adapted high-yielding varieties. Sowing under zero tillage and raised bed systems was carried out using zero-till cum bed planters, respectively, ensuring uniform seed placement and depth. In residue retention treatments, crop residues from the preceding rice crop were retained and evenly spread over the soil surface. In contrast, residues were removed in conventional tillage plots. A uniform fertilizer dose of 150:60:40 kg N: P₂O₅: K₂O ha⁻¹ was applied across all treatments based on regional recommendations. Nitrogen was applied in three splits (basal, first irrigation, and second irrigation), while phosphorus and potassium were applied as basal doses. Irrigation scheduling was based on critical growth stages, including crown root initiation, tillering, jointing, flowering, and grain filling. The number of irrigations varied between 3 and 5 depending on treatment, with reduced irrigation frequency in residue-retained and raised bed systems.

Observations on crop growth, yield attributes, and grain yield were recorded using standard agronomic procedures. Crop water productivity (CWP) was computed as the ratio of grain yield (kg ha⁻¹) to total water input (irrigation water plus effective rainfall), expressed in kg m⁻³. Grain quality parameters, including protein content, test weight, and gluten content, was analyzed using standard laboratory protocols. Soil sampling was conducted from the 0–15 cm depth at the initiation of the study and after each cropping season. Soil organic carbon was determined using the Walkley–Black method, while microbial biomass carbon

was estimated through the fumigation-extraction method. Bulk density was measured using the core sampler method. Infiltration rate was assessed using a double-ring infiltrometer, and aggregate stability was determined through wet sieving.

For artificial intelligence-based evaluation, a comprehensive database was generated incorporating soil properties, crop parameters, weather data, irrigation inputs, and residue levels. Machine learning models, including random forest, support vector machine, and artificial neural networks, were employed to analyze and predict crop water productivity, grain yield, and soil health indicators. Farmers' field data served as independent observations, enhancing model generalization. The dataset was divided into training (70%) and validation (30%) sets. Model performance was evaluated using statistical metrics such as coefficient of determination (R²), root mean square error (RMSE), and mean absolute error (MAE). Additionally, remote sensing data were integrated to capture spatial variability across farmer fields. Vegetation indices such as normalized difference vegetation index (NDVI) were derived and used as auxiliary inputs in AI models.

Statistical analysis of field data was performed using analysis of variance (ANOVA) appropriate for RBD, considering farmers as replications. Combined analysis over years and locations was carried out to evaluate temporal stability and spatial consistency of treatment effects. This integrated methodology combining farmer-participatory experimentation, long-term field data, and AI-based modeling provided a robust framework for assessing the sustainability and efficiency of conservation agriculture practices in wheat-based systems of Typic Ustochrept soils.

Results and Discussion

Table 1: Long-term influence of conservation agriculture practices on wheat productivity, yield attributes and biomass partitioning in western Uttar Pradesh

Treatment	Tillers (m ⁻²)			Grains spike ⁻¹			Test weight (g)			Grain yield (t ha ⁻¹)			Biological yield (t ha ⁻¹)			Harvest index %		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	320	335	330	42	44	43	38.5	39.0	39.2	4.45	4.52	4.58	10.2	10.6	10.9	43.6	42.6	42.0
T ₂ : ZT-R	335	355	370	44	47	49	39.5	40.5	41.0	4.60	4.85	5.00	11.0	11.4	11.8	41.8	42.5	42.5
T ₃ : ZT+R	350	380	400	46	50	52	40.5	41.8	42.5	4.75	5.10	5.35	11.8	12.3	12.8	40.3	41.5	43.0
T ₄ : FIRB-R	345	370	385	45	48	50	40.2	41.2	42.0	4.70	5.00	5.25	11.5	12.0	12.4	40.8	41.7	42.8
T ₅ : FIRB+R	360	395	410	47	52	54	41.0	42.5	43.8	4.85	5.35	5.72	12.2	13.0	13.8	39.7	41.2	43.5
CD (0.05)	24	30	36	3.6	4.5	5.4	1.8	1.9	1.7	0.24	0.30	0.35	0.60	0.75	0.90	-	-	-

The results clearly demonstrate that conservation agriculture (CA) practices significantly improved wheat yield and associated yield attributes over the study period (2015–2025). Among the treatments, T₅ (FIRB + residue retention) consistently recorded the highest grain yield, increasing from 4.85 t ha⁻¹ in 2015 to 5.72 t ha⁻¹ in 2025. This represents an increase of approximately 28% over conventional tillage (T₁), which showed stagnation and even slight decline in productivity, over time (4.45 to 4.58 t ha⁻¹). Similarly, biological yield followed a parallel trend, with T₅ reaching 13.8 t ha⁻¹ in 2025 compared to 10.9 t ha⁻¹ under T₁. Yield attributes such as tiller density, grains per spike, and test weight were significantly enhanced under CA practices. Tiller density increased from 320 m⁻² under CT to 410 m⁻² under T₅ in 2025. Grains per spike increased from

42 to 54, while 1000-grain weight improved from 38.5 g to 44.0 g.

Harvest index also improved under CA, indicating better partitioning of assimilates towards economic yield. Treatments involving residue retention (T₃ and T₅) consistently outperformed those without residue, highlighting the importance of crop residue management. The standard error and CD values confirmed that these differences were statistically significant across years.

The substantial improvement in wheat productivity under CA practices can be attributed to multiple interacting factors, including enhanced soil moisture conservation, improved soil structure, and increased nutrient availability. Residue retention plays a critical role in reducing evaporation losses and maintaining favorable soil

temperature, thereby promoting better crop growth (Lal, 2015) [15]. The higher tiller density and grain number observed under CA treatments suggest improved crop establishment and nutrient uptake efficiency. Jat *et al.* (2014) [11], zero tillage combined with residue retention improves early crop vigor, leading to higher yield components.

Naresh *et al.* (2017) [17] emphasized that long-term adoption of CA enhances rhizospheric activity and soil biological processes, which contribute to sustained yield improvement.

The increase in 1000-grain weight indicates better grain filling due to prolonged availability of soil moisture during critical growth stages. Furrow irrigated raised bed (FIRB) systems further enhance productivity by improving water distribution and reducing waterlogging, thereby promoting root growth and nutrient uptake (Humphreys *et al.*, 2010) [10]. In contrast, conventional tillage leads to soil degradation, reduced organic matter, and compaction, which negatively affect crop performance over time.

Table 2: Impact of conservation agriculture on irrigation water use, water productivity and water-saving efficiency in wheat-based systems

Treatment	Irrigation			WUE			Water productivity			Consumptive use			Irrigation efficiency			IW/CPE ratio		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	520	510	505	6.8	7.0	7.3	1.20	1.28	1.35	600	595	590	65	65	65	0.90	0.88	0.85
T ₂ : ZT-R	500	480	460	7.5	8.2	8.8	1.35	1.48	1.60	570	560	550	68	70	70	0.85	0.82	0.80
T ₃ : ZT+R	480	450	420	8.5	9.6	10.5	1.50	1.70	1.90	540	520	500	70	73	75	0.80	0.75	0.70
T ₄ : FIRB-R	470	440	410	8.2	9.2	10.0	1.45	1.65	1.80	530	510	495	69	72	73	0.82	0.78	0.72
T ₅ : FIRB+R	455	420	395	9.0	10.8	12.2	1.60	1.85	2.15	510	490	470	72	75	78	0.78	0.72	0.65
CD (0.05)	30	35	45	0.9	1.2	1.5	0.15	0.18	0.24	45	45	45	6	6	6	-	-	-

The data indicate that conservation agriculture practices significantly reduced irrigation water use while enhancing water productivity. Conventional tillage (T₁) required the highest irrigation (520 mm in 2015 and 505 mm in 2025), whereas T₅ required the least (455 mm in 2015 and 395 mm in 2025). This reflects water saving of up to 22% under CA systems. Total water use followed a similar pattern, with T₅ recording the lowest values (535–470 mm) compared to T₁ (610–595 mm). Water use efficiency (WUE) improved substantially under CA treatments, increasing from 9.0 kg ha⁻¹ mm⁻¹ in T₁ to 12.2 kg ha⁻¹ mm⁻¹ in T₅ by 2025. Water productivity also showed significant improvement; with T₅ achieving 2.15 kg m⁻³ compared to 1.35 kg m⁻³ under CT. Treatments with residue retention (T₃ and T₅) consistently exhibited higher WUE and water productivity than those without residue. Statistical analysis indicated that these differences were significant.

The improvement in water productivity under CA practices is primarily due to enhanced soil moisture conservation and reduced evaporation losses. Residue mulch acts as a protective layer on the soil surface, minimizing direct

evaporation and improving water infiltration (Rockström *et al.*, 2010) [25]. Zero tillage further contributes to improved soil structure, leading to increased infiltration rates and reduced runoff. Naresh *et al.* (2018) [20] reported that CA practices can reduce irrigation requirements by 15–25% in wheat-based systems of western Uttar Pradesh. The present findings are consistent with these observations. The higher WUE observed under FIRB systems can be attributed to efficient water application and reduced water losses. Jat *et al.* (2019) [12] revealed that in raised bed planting improves irrigation efficiency by optimizing water distribution and reducing deep percolation.

Improved soil organic matter under CA enhances soil water holding capacity, ensuring better crop performance during dry periods (Farooq *et al.*, 2011) [7]. The combination of residue retention and reduced tillage creates a favorable soil environment that supports efficient water use. These results highlight the potential of CA practices in addressing water scarcity challenges and improving irrigation efficiency in semi-arid regions.

Table 3: Dynamics of soil organic carbon pools and fractions under conservation agriculture practices in ustochrept soil

Treatment	SOC (%)			Labile C (%)			POC (%)			DOC (mg kg ⁻¹)			Passive C (%)			C stock (Mg ha ⁻¹)		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	0.38	0.40	0.41	0.10	0.11	0.12	0.12	0.14	0.15	40	45	48	0.22	0.24	0.25	18.5	19.0	19.5
T ₂ : ZT-R	0.42	0.48	0.52	0.14	0.16	0.18	0.15	0.18	0.20	45	50	55	0.26	0.28	0.30	20.5	22.0	23.5
T ₃ : ZT+R	0.45	0.55	0.62	0.18	0.21	0.23	0.18	0.23	0.26	50	58	65	0.28	0.32	0.34	22.5	25.5	28.0
T ₄ : FIRB-R	0.44	0.52	0.58	0.17	0.19	0.21	0.17	0.21	0.24	48	55	62	0.27	0.30	0.32	21.8	24.0	26.5
T ₅ : FIRB+R	0.48	0.60	0.68	0.20	0.24	0.26	0.20	0.26	0.30	52	62	75	0.30	0.34	0.36	23.5	27.5	31.0
CD (0.05)	0.03	0.05	0.06	0.03	0.03	0.03	0.03	0.03	0.03	6	9	9	0.03	0.03	0.03	2.4	3.0	3.6

Table 3 indicated that conservation agriculture (CA) practices significantly improved soil organic carbon (SOC) and its various fractions over the experimental period (2015–2025). Among the treatments, T₅ (FIRB with residue retention) consistently recorded the highest SOC values, increasing from 0.48% in 2015 to 0.68% in 2025. In contrast, conventional tillage (T₁) showed relatively lower SOC levels, increasing marginally from 0.38% to 0.41% during the same period.

The labile carbon fraction, which represents the active and easily decomposable pool, showed a marked increase under CA treatments. T₅ recorded an increase from 0.20% in 2015 to 0.26% in 2025, whereas T₁ remained relatively low (0.10–0.12%). Similarly, particulate organic carbon (POC) increased significantly under residue-retained treatments, reaching 0.30% under T₅ compared to 0.15% under CT in 2025. Dissolved organic carbon (DOC), which is important for microbial activity, also increased from 52 mg kg⁻¹ to 75 mg kg⁻¹ under T₅, while CT recorded only 40–48 mg kg⁻¹.

Passive carbon fractions, which represent the stable and long-term carbon pool, showed gradual improvement under CA practices. T_5 recorded an increase from 0.30% to 0.36%, indicating enhanced carbon stabilization. Residue-retained treatments (T_3 and T_5) consistently outperformed non-residue treatments, demonstrating the importance of crop residue management in maintaining soil carbon pools. Statistical analysis indicated that differences among treatments were significant for all carbon fractions.

The significant increase in SOC and its fractions under CA practices is primarily attributed to continuous addition of crop residues and reduced soil disturbance. Residue retention enhances carbon inputs into the soil, while reduced tillage minimizes oxidation losses, leading to net carbon accumulation. This finding is consistent with Lal (2015) [15], who emphasized that CA systems play a crucial role in carbon sequestration and soil restoration.

Nareish *et al.* (2016) [22] reported that long-term adoption of CA practices in the Indo-Gangetic Plains increased SOC by 20–40%, which aligns well with the present findings. The increase in labile carbon fractions under CA indicates improved soil biological activity and nutrient cycling, as this

fraction serves as an immediate energy source for soil microorganisms. Enhanced microbial activity further accelerates decomposition and nutrient mineralization processes. The substantial increase in particulate organic carbon (POC) reflects improved aggregation and physical protection of organic matter within soil aggregates. Six *et al.* (2002) [26], reported that CA practices promote aggregate formation, which stabilizes organic carbon and protects it from rapid decomposition. The increase in DOC under CA treatments indicates improved soil solution dynamics and availability of soluble organic compounds, which are essential for microbial metabolism.

The gradual increase in passive carbon fractions suggests long-term stabilization of carbon in the soil, contributing to improved soil resilience and sustainability. In contrast, conventional tillage disrupts soil aggregates and accelerates organic matter decomposition, leading to lower SOC levels. Therefore, the results demonstrate that CA practices, particularly when combined with residue retention, significantly enhance soil carbon pools, improve soil health, and contribute to climate change mitigation through increased carbon sequestration.

Table 4: Response of soil microbial biomass and enzymatic activities to long-term conservation agriculture interventions

Treatment	MBC			MBN			MBP			Dehydrogenase			Urease			Phosphatase		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T_1 : CT	180	185	190	25	26	28	14	15	16	18	19	20	30	31	32	22	24	25
T_2 : ZT–R	200	215	230	28	30	32	16	18	20	22	24	26	34	36	38	26	28	30
T_3 : ZT+R	240	265	290	32	35	38	18	20	22	26	29	32	40	42	45	30	34	36
T_4 : FIRB–R	230	250	270	30	33	36	17	19	21	25	27	30	38	40	42	28	32	34
T_5 : FIRB+R	260	295	330	34	38	42	20	23	25	28	33	38	42	46	50	32	36	40
CD (0.05)	24	30	36	6	6	6	6	6	6	6	6	6	9	9	9	6	6	6

The data (Table 4) revealed a substantial improvement in soil microbial biomass and enzymatic activities under conservation agriculture (CA) practices over the experimental period (2015–2025). Microbial biomass carbon (MBC) increased significantly across CA treatments, with T_5 (FIRB + residue retention) recording the highest values, rising from 260 mg kg⁻¹ in 2015 to 330 mg kg⁻¹ in 2025. In contrast, conventional tillage (T_1) exhibited relatively stagnant values (180–190 mg kg⁻¹). Similarly, microbial biomass nitrogen (MBN) and phosphorus (MBP) followed comparable trends, with T_5 showing maximum increases (MBN: 34 to 42 mg kg⁻¹; MBP: 20 to 25 mg kg⁻¹). Enzymatic activities, including dehydrogenase, urease, and phosphatase, showed significant enhancement under CA treatments. Dehydrogenase activity increased from 28 to 38 µg TPF g⁻¹ soil day⁻¹ in T_5 , while urease and phosphatase activities also showed consistent improvements. Residue-retained treatments (T_3 and T_5) consistently outperformed non-residue treatments, indicating the importance of organic inputs. Statistical analysis confirmed that differences among treatments were significant. The enhancement in microbial biomass and enzyme activity under CA systems is primarily

attributed to increased organic matter input and improved soil microclimate. Residue retention provides a continuous supply of carbon substrates, which stimulate microbial growth and activity (Doran, 1980) [6]. Nareish *et al.* (2019) [12] reported that long-term CA practices significantly increase microbial biomass due to improved soil organic carbon and reduced disturbance. The higher enzymatic activity observed under CA reflects enhanced nutrient cycling and soil fertility, as enzymes play a critical role in organic matter decomposition and nutrient mineralization (Nannipieri *et al.*, 2012) [16].

Dehydrogenase activity is an indicator of overall microbial activity and was significantly higher under CA, suggesting improved biological functioning of soil. Urease and phosphatase activities are directly related to nitrogen and phosphorus cycling, respectively, indicating improved nutrient availability under CA systems. Reduced microbial activity under conventional tillage may be due to soil disturbance and rapid oxidation of organic matter. These findings confirm that CA practices improve soil biological health, which is essential for sustainable crop production.

Table 5: Changes in soil physical properties, aggregation and water retention characteristics under conservation agriculture systems

Treatment	Bulk density			Porosity (%)			Infiltration (cm hr ⁻¹)			WHC (%)			Aggregate stability (%)			MWD		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T_1 : CT	1.58	1.60	1.62	40	40.5	41	1.5	1.6	1.7	38	39	40	35	36	38	0.40	0.42	0.45
T_2 : ZT–R	1.52	1.50	1.50	43	44	44	1.8	2.0	2.2	40	42	44	45	47	48	0.50	0.53	0.55
T_3 : ZT+R	1.48	1.45	1.42	45	47	48	2.2	2.6	3.0	42	46	49	52	57	60	0.60	0.65	0.70
T_4 : FIRB–R	1.50	1.48	1.45	44	45	46	2.0	2.4	2.8	41	44	47	50	53	55	0.55	0.60	0.65
T_5 : FIRB+R	1.48	1.42	1.38	45	48	50	2.4	3.0	3.6	43	48	52	55	60	65	0.60	0.68	0.75
CD (0.05)	0.09	0.09	0.09	3	3.5	3.5	0.6	0.6	0.6	4.5	4.5	4.5	6	6	6	-	-	-

Table 5 demonstrated that conservation agriculture (CA) practices significantly improved soil physical properties over the experimental period (2015–2025). Among the treatments, T₃ (furrow irrigated raised beds with residue retention) consistently recorded the most favorable soil physical conditions compared to conventional tillage (T₁). Bulk density, a key indicator of soil compaction, decreased progressively under CA treatments. In T₃, bulk density reduced from 1.48 Mg m⁻³ in 2015 to 1.38 Mg m⁻³ in 2025, whereas in T₁ it increased from 1.58 to 1.62 Mg m⁻³, indicating progressive soil degradation under conventional practices.

Soil porosity exhibited an inverse trend to bulk density and improved significantly under CA systems. T₃ recorded an increase in porosity from 45% in 2015 to 50% in 2025, compared to a marginal increase under CT (40–41%). Infiltration rate showed a marked improvement under CA, nearly doubling in T₃ from 3.0 cm h⁻¹ in 2015 to 3.6 cm h⁻¹ in 2025, while CT showed minimal improvement (1.5–1.7 cm h⁻¹). Water holding capacity (WHC) increased significantly under CA, with T₃ recording values from 43% to 52%, compared to 38–40% under CT.

Aggregate stability, an important indicator of soil structural integrity, improved substantially under CA treatments. T₃ recorded aggregate stability values increasing from 55% in 2015 to 65% in 2025, whereas CT showed lower values (35–38%). Mean weight diameter (MWD) of soil aggregates also increased significantly under CA, indicating better aggregation.

Residue-retained treatments (T₃ and T₅) consistently performed better than non-residue treatments, highlighting the role of residue management in improving soil structure. Over time, improvements in soil physical properties became more pronounced under CA systems. Statistical analysis indicated that all differences among treatments were significant.

The observed improvements in soil physical properties under CA practices can be attributed to reduced soil disturbance, increased organic matter input, and enhanced biological activity. Reduced tillage helps maintain soil structure and prevents the breakdown of aggregates, while

residue retention adds organic matter that acts as a binding agent for soil particles. This is consistent with the findings of Bronick and Lal (2005) [4], who emphasized the role of organic matter in improving soil aggregation and structure.

Naresh *et al.* reported significant improvements in soil physical properties under long-term CA practices in western Uttar Pradesh, including reductions in bulk density and increases in porosity and infiltration rate. The present results strongly support these findings, as T₃ consistently showed the most favorable soil physical conditions.

The reduction in bulk density under CA is mainly due to increased organic matter and improved aggregation, which create a more porous soil structure. Lower bulk density facilitates root penetration and enhances water and nutrient movement within the soil. Increased porosity further improves soil aeration and water infiltration, creating a favorable environment for plant growth.

The significant increase in infiltration rate under CA is particularly important in reducing runoff and improving water use efficiency. Residue mulch protects the soil surface from raindrop impact, preventing surface sealing and promoting water entry into the soil. According to Blanco-Canqui and Lal (2008) [2], residue retention significantly enhances infiltration and reduces soil erosion.

Improved water holding capacity under CA is attributed to higher organic matter content, which increases the soil's ability to retain moisture. This is especially beneficial in semi-arid regions, where water availability is a major constraint.

The enhancement in aggregate stability and MWD under CA indicates improved soil structural stability, which reduces susceptibility to erosion and degradation. Six *et al.* (2002) [26], also found that CA practices promote the formation of stable soil aggregates, which protect organic carbon and improve soil resilience.

In contrast, conventional tillage disrupts soil aggregates, accelerates organic matter decomposition, and increases compaction, leading to poor soil physical conditions. Frequent tillage operations also create a plough pan, which restricts root growth and water movement.

Table 6: Effect of conservation agriculture practices on wheat grain quality parameters and end-use characteristics

Treatment	Protein (%)			Gluten (%)			Sedimentation value			Starch (%)			Grain hardness			Test weight (g)		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	11.2	11.3	11.3	24.5	25.0	25.2	30	31	32	69	68.5	68	63	64	65	38.5	39.0	39.2
T ₂ : ZT–R	11.5	11.8	12.0	26.0	27.0	27.5	32	34	35	68	67.5	67	65	67	68	39.5	40.5	41.0
T ₃ : ZT+R	12.0	12.5	13.0	28.0	29.5	30.5	35	38	40	67	66	65	68	70	72	40.5	41.8	42.5
T ₄ : FIRB–R	11.8	12.2	12.7	27.5	28.5	29.0	34	36	38	67.5	66.5	66	67	69	70	40.2	41.2	42.0
T ₅ : FIRB+R	12.0	13.0	13.8	29.0	31.0	32.5	36	40	43	66	65	64	70	73	75	41.0	42.5	43.8
CD (0.05)	0.9	0.9	0.9	2.4	2.4	2.4	4.5	4.5	4.5	3	3	3	6	6	6	1.8	1.8	1.8

Table 6 revealed that conservation agriculture (CA) practices significantly influenced wheat grain quality parameters over the experimental period (2015–2025). Among the treatments, T₅ (furrow irrigated raised beds with residue retention) consistently recorded the highest values for all major quality traits. Grain protein content under T₅ increased from 12.0% in 2015 to 13.8% in 2025, whereas conventional tillage (T₁) showed minimal improvement, remaining around 11.2–11.3% during the same period.

Gluten content, an important indicator of dough elasticity and baking quality, also showed a substantial increase under

CA treatments. T₅ recorded an increase from 29.5% in 2015 to 32.5% in 2025, compared to only 24.5–25.2% under T₁. Similarly, sedimentation value, which reflects protein quality and gluten strength, improved significantly under CA practices, with T₅ recording values from 36 to 43 ml over the study period, while CT remained lower at 30–32 ml.

Test weight, which is a measure of grain density and overall grain development, increased from 41.0 g to 43.8 g under T₅, whereas CT showed relatively lower values (38.5–39.2 g). Residue-retained treatments (T₃ and T₅) consistently

outperformed non-residue treatments (T_2 and T_4), indicating the positive role of residue management in enhancing grain quality.

Interestingly, starch content exhibited a slight decline under CA treatments, decreasing from 66% in CT to around 64% under T_5 by 2025. This suggests a shift in assimilate partitioning towards protein synthesis. Overall, statistical analysis confirmed that differences among treatments were significant across years.

The improvement in wheat grain quality under CA practices can be attributed to enhanced nutrient availability, particularly nitrogen, and improved soil moisture conditions during the grain filling stage. Increased nitrogen uptake under CA systems leads to higher protein synthesis, which directly enhances grain protein content and gluten formation. These findings are in agreement with Gooding *et al.* (2003) [9], who reported that nitrogen availability during grain filling plays a crucial role in determining wheat protein content.

Naresh *et al.* (2020) also observed significant improvements in wheat grain quality under long-term CA practices due to enhanced soil fertility and nutrient cycling. Residue retention contributes to gradual mineralization of nutrients, ensuring a continuous supply of nitrogen and other essential elements throughout the crop growth period. This results in

improved grain filling and higher accumulation of storage proteins. The increase in gluten content and sedimentation value under CA treatments indicates improved end-use quality, particularly for bread-making purposes. Triboi *et al.* (2006) observed that grain protein composition and quality are strongly influenced by environmental conditions and nutrient availability, both of which are optimized under CA systems.

The observed increase in test weight under CA reflects better grain development due to prolonged grain filling duration and improved moisture availability. Residue mulch reduces soil temperature fluctuations and conserves moisture, which enhances physiological processes during grain development.

The slight reduction in starch content under CA treatments suggests a redistribution of assimilates towards protein synthesis rather than carbohydrate accumulation. This is often observed under improved nitrogen management and favorable growth conditions. In contrast, conventional tillage systems tend to have lower nutrient use efficiency and poorer soil moisture conditions, which limit protein synthesis and grain quality. Soil degradation and reduced organic matter under CT further exacerbate these limitations.

Table 7: Nutrient uptake, nutrient use efficiency and macro-nutrient dynamics under conservation agriculture practices

Treatment	N uptake (kg ha ⁻¹)			P uptake			K uptake			S uptake			NUE (%)			PUE (%)		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T_1 : CT	88	90	93	18	19	20	95	100	105	10	11	12	32	33	35	25	26	28
T_2 : ZT-R	95	105	110	20	23	25	105	115	120	11	13	14	35	38	40	28	30	32
T_3 : ZT+R	105	115	125	22	26	30	115	130	140	12	14	16	38	42	45	30	33	36
T_4 : FIRB-R	100	110	120	21	24	28	110	125	135	11	13	15	36	40	43	29	32	34
T_5 : FIRB+R	105	125	140	23	28	32	120	140	150	12	15	18	40	45	50	32	35	38

Table 7 clearly demonstrated that among the treatments, T_5 (furrow irrigated raised beds with residue retention) consistently recorded the highest uptake of major nutrients, including nitrogen (N), phosphorus (P), potassium (K), and sulfur (S).

Nitrogen uptake under T_5 increased substantially from 105 kg ha⁻¹ in 2015 to 140 kg ha⁻¹ in 2025, whereas conventional tillage (T_1) showed comparatively lower values, ranging from 88 to 93 kg ha⁻¹. Phosphorus uptake followed a similar trend, increasing from 23 kg ha⁻¹ to 32 kg ha⁻¹ under T_5 , while T_1 recorded only 18–20 kg ha⁻¹. Potassium uptake also showed a marked improvement under CA, with T_5 increasing from 120 to 150 kg ha⁻¹ compared to 95–105 kg ha⁻¹ under CT. Sulfur uptake increased from 12 to 18 kg ha⁻¹ under T_5 , while CT recorded lower values (10–12 kg ha⁻¹).

Nutrient use efficiency showed a significant improvement under CA treatments. Nitrogen use efficiency (NUE) increased from 408% in 2015 to 50% in 2025 under T_5 , whereas CT remained relatively low (32–35%). Phosphorus use efficiency (PUE) and potassium use efficiency (KUE) also followed similar trends, with CA treatments showing consistently higher efficiency compared to conventional practices.

Residue-retained treatments (T_3 and T_5) performed significantly better than treatments without residue, indicating the critical role of residue management in nutrient dynamics. Over time, the gap between CA and CT widened, reflecting cumulative benefits of CA practices. Statistical

analysis confirmed that the differences in nutrient uptake and use efficiency among treatments were significant across all years.

The enhanced nutrient uptake under CA practices can be attributed to improved soil physical, chemical, and biological properties, which collectively create a favorable environment for nutrient availability and plant uptake. Residue retention plays a crucial role by adding organic matter to the soil, which upon decomposition releases nutrients gradually and improves nutrient cycling efficiency. This is consistent with findings of Cassman *et al.* (2002), who emphasized the importance of synchronized nutrient release for improved crop uptake.

Naresh *et al.* (2018) reported that CA practices significantly improve nutrient use efficiency in wheat systems due to better synchronization between nutrient supply and crop demand. The present findings corroborate these results, as T_5 showed the highest NUE, indicating efficient utilization of applied fertilizers.

Improved soil organic carbon under CA enhances cation exchange capacity and nutrient retention, reducing nutrient losses through leaching and volatilization. This leads to higher nutrient availability in the root zone. Additionally, increased microbial biomass and enzymatic activity under CA facilitate nutrient mineralization, making nutrients more available to plants (Nannipieri *et al.*, 2012).

Root growth also plays a significant role in nutrient uptake. Enhanced root length and biomass under CA enable plants to explore a larger soil volume, thereby increasing nutrient

absorption. Naresh *et al.* (2017) highlighted that improved root architecture under CA contributes significantly to higher nutrient uptake.

The improvement in phosphorus uptake under CA may also be linked to increased phosphatase activity, which enhances the availability of phosphorus from organic sources. Similarly, better potassium uptake is associated with improved soil structure and moisture availability, which facilitate nutrient mobility.

The higher NUE observed under CA is particularly important from an environmental perspective, as it reduces fertilizer losses and minimizes environmental pollution.

According to Ladha *et al.* (2016), improving NUE is essential for sustainable agricultural intensification.

In contrast, conventional tillage systems often suffer from nutrient losses due to poor soil structure, low organic matter, and inefficient fertilizer use. Frequent soil disturbance disrupts microbial activity and accelerates nutrient loss, leading to lower nutrient uptake and efficiency. However, the results clearly indicate that CA practices, particularly when combined with residue retention, significantly enhance nutrient uptake and use efficiency in wheat by improving soil health, microbial activity, and root growth. These improvements contribute to higher productivity and sustainability of the cropping system

Table 8: Root growth dynamics and below-ground biomass development of wheat as influenced by conservation agriculture

Treatment	Root length (cm)			Root biomass (t ha ⁻¹)			Root density			Root volume (cm ³)			Root depth (cm)			Root: shoot ratio		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	16	17	18	1.0	1.1	1.2	0.40	0.42	0.45	18	19	20	28	29	30	0.22	0.24	0.25
T ₂ : ZT-R	18	20	22	1.2	1.3	1.5	0.45	0.50	0.55	20	23	25	30	33	35	0.24	0.26	0.28
T ₃ : ZT+R	20	23	26	1.5	1.7	2.0	0.50	0.60	0.70	24	28	32	34	38	42	0.26	0.29	0.32
T ₄ : FIRB-R	19	22	24	1.4	1.6	1.8	0.48	0.58	0.65	22	26	30	32	36	40	0.25	0.28	0.30
T ₅ : FIRB+R	21	25	28	1.6	1.9	2.2	0.52	0.65	0.75	26	30	35	35	40	45	0.27	0.31	0.34
CD (0.05)	3	3	3	0.3	0.3	0.3	0.09	0.09	0.09	6	6	6	6	6	6	-	-	-

The results clearly demonstrated that conservation agriculture (CA) practices significantly improved root growth parameters and below-ground biomass over the experimental period (2015–2025). Among all treatments, T₅ (furrow irrigated raised beds with residue retention) consistently recorded the highest values for root length, root density, root volume, and root biomass. Root length under T₅ increased from 21 cm in 2015 to 28 cm in 2025, whereas conventional tillage (T₁) recorded comparatively lower values, increasing marginally from 16 cm to 18 cm during the same period.

Root biomass showed a substantial improvement under CA systems. T₅ recorded an increase from 1.6 t ha⁻¹ in 2015 to 2.2 t ha⁻¹ in 2025, while T₁ remained relatively low (1.1–1.2 t ha⁻¹). Root density and root volume followed similar trends, with CA treatments, particularly those with residue retention (T₃ and T₅), showing significantly higher values compared to non-residue treatments (T₂ and T₄).

Root depth distribution also improved under CA practices, with a greater proportion of roots penetrating deeper soil layers (20–40 cm and beyond). In contrast, roots under CT were mostly confined to the upper soil layers (0–15 cm), indicating restricted root growth. The root: shoot ratio increased slightly under CA treatments, reflecting better allocation of biomass below ground.

Temporal trends indicated that improvements in root parameters became more pronounced over time, especially after 3–5 years of continuous CA adoption. Statistical analysis confirmed that differences among treatments were significant for all root parameters across years.

The significant improvement in root growth under CA practices can be attributed to enhanced soil physical conditions, increased organic matter content, and improved soil moisture availability. Reduced soil disturbance under zero tillage and raised bed systems helps maintain soil structure, allowing roots to penetrate deeper into the soil profile. This is consistent with findings of Bengough *et al.* (2011), who reported that reduced mechanical impedance facilitates root elongation and development.

Naresh *et al.* (2017) observed that CA practices significantly enhance root growth and distribution in wheat due to improved soil porosity and reduced bulk density. The present results strongly support these findings, as T₅ recorded the lowest bulk density and highest porosity, which are favorable conditions for root proliferation.

Residue retention plays a crucial role in improving root growth by maintaining soil moisture and temperature. Surface residues reduce evaporation losses and moderate soil temperature fluctuations, creating a favorable environment for root activity. This leads to prolonged root growth and better exploration of soil resources. According to Blanco-Canqui and Lal (2008), residue mulch enhances soil moisture retention, which directly influences root development.

The increase in root biomass under CA is also linked to improved nutrient availability. Enhanced microbial activity and organic matter decomposition release nutrients in plant-available forms, which stimulate root growth. A well-developed root system further enhances nutrient uptake, creating a positive feedback mechanism.

The deeper root penetration observed under CA treatments is particularly important in improving drought resilience. Deeper roots can access water and nutrients from deeper soil layers, ensuring better crop performance under water-limited conditions. This is especially relevant in the semi-arid regions of western Uttar Pradesh.

In contrast, conventional tillage systems often lead to soil compaction and formation of plough pans, which restrict root growth. Frequent soil disturbance also disrupts soil structure and microbial activity, negatively affecting root development.

The improvement in root:shoot ratio under CA indicates better allocation of biomass towards roots, which enhances the plant's ability to absorb water and nutrients. This contributes to improved crop productivity and resource use efficiency.

Overall, the results clearly demonstrate that CA practices, particularly FIRB with residue retention, significantly

improve root growth parameters and below-ground biomass. These improvements play a critical role in enhancing nutrient uptake, water use efficiency, and overall crop

productivity, making CA a sustainable approach for wheat cultivation in the Indo-Gangetic Plains.

Table 9: Economic viability, profitability and benefit–cost analysis of conservation agriculture practices in wheat cultivation

Treatment	Cost of cultivation (Rs. ha ⁻¹)			Gross return (Rs. ha ⁻¹)			Net return (Rs. ha ⁻¹)			B:C ratio			Profitability (Rs. ha ⁻¹ day ⁻¹)			Economic efficiency (Rs. ha ⁻¹ day ⁻¹)		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	52000	54000	56000	100000	105000	110000	48000	51000	54000	1.92	1.94	1.96	300	320	340	310	330	350
T ₂ : ZT–R	50000	51500	53000	110000	118000	125000	60000	66500	72000	2.20	2.29	2.36	375	415	450	390	430	470
T ₃ : ZT+R	48000	49500	51000	120000	130000	140000	72000	80500	89000	2.50	2.63	2.75	450	505	560	470	530	590
T ₄ : FIRB–R	49000	50500	52000	118000	128000	138000	69000	77500	86000	2.41	2.53	2.65	430	485	540	450	510	570
T ₅ : FIRB+R	48000	49500	51000	125000	138000	150000	77000	88500	99000	2.60	2.79	2.94	480	555	620	500	580	650
CD (0.05)	3600	3900	4200	7500	9000	9600	6000	6600	7500	0.24	0.27	0.30	45	54	60	-	-	-

The economic evaluation over the experimental period (able 9) clearly indicated that conservation agriculture (CA) practices significantly improved the profitability of wheat cultivation compared to conventional tillage (T₁). Among the treatments, T₅ (furrow irrigated raised beds with residue retention) consistently recorded the highest economic returns across all study years. The cost of cultivation under conventional tillage remained higher, ranging from Rs. 52,000 ha⁻¹ in 2015 to Rs. 56,000 ha⁻¹ in 2025, primarily due to repeated tillage operations, higher fuel consumption, and increased labor requirements. In contrast, CA treatments, especially T₅, reduced the cost of cultivation to Rs. 48,000–Rs. 51,000 ha⁻¹ due to fewer field operations and lower energy inputs.

Gross returns were significantly higher under CA practices. T₅ recorded gross returns of Rs. 125,000 ha⁻¹ in 2015, which increased to Rs. 150,000 ha⁻¹ in 2025, reflecting the higher grain and biomass yield obtained under this treatment. Conventional tillage, however, showed relatively lower and stagnant gross returns (Rs. 100,000–Rs. 110,000 ha⁻¹). Net returns followed a similar trend, with T₅ achieving the highest net return of Rs. 99,000 ha⁻¹ in 2025, compared to only Rs. 54,000 ha⁻¹ under T₁.

The benefit–cost (B: C) ratio improved markedly under CA treatments. T₅ recorded the highest B: C ratio, increasing from 2.60 in 2015 to 2.94 in 2025, while conventional tillage recorded lower values ranging from 1.92 to 1.96. Treatments with residue retention (T₃ and T₅) consistently outperformed those without residue (T₂ and T₄), indicating the economic advantage of residue management. Over time, the profitability gap between CA and CT widened, demonstrating the cumulative benefits of CA practices. Statistical analysis confirmed that differences among treatments were significant for all economic parameters.

The higher economic returns observed under CA practices are primarily attributed to reduced production costs and increased crop productivity. Reduced tillage operations significantly lower fuel consumption, labor requirements, and machinery use, thereby decreasing the overall cost of cultivation. This finding aligns with Jat *et al.* (2014) [11], who reported that CA practices can reduce operational costs

by 10–20% compared to conventional tillage systems. Naresh *et al.* (2019) [20] also observed that long-term adoption of CA practices in western Uttar Pradesh led to substantial improvements in farm profitability due to lower input costs and higher yields. The present results strongly support these findings, as T₅ consistently recorded the highest net returns and B:C ratio throughout the study period.

Residue retention plays a crucial role in enhancing economic returns by improving soil fertility and reducing the need for external inputs such as fertilizers and irrigation. Improved soil organic carbon and nutrient availability under CA reduce input requirements while maintaining high productivity levels. Gathala *et al.* (2013) [8] also reported higher profitability under CA due to improved soil health and resource use efficiency. The increase in gross returns under CA treatments is mainly driven by higher grain yield and improved crop performance. Enhanced water use efficiency, better nutrient uptake, and improved soil physical conditions under CA contribute to increased productivity, which directly translates into higher economic returns.

The improvement in B: C ratio under CA indicates better economic efficiency and sustainability. A higher B:C ratio reflects greater returns per unit investment, making CA practices more attractive and economically viable for farmers. This is particularly important in regions with limited resources, where cost reduction and efficiency are critical. Additionally, the long-term benefits of CA, such as improved soil health and reduced environmental degradation, further enhance its economic sustainability. Although initial adoption of CA may require investment in specialized machinery, the long-term gains in productivity and cost savings outweigh these initial costs.

In contrast, conventional tillage systems are associated with higher costs and lower efficiency due to soil degradation, increased input requirements, and lower productivity. Frequent tillage operations not only increase costs but also negatively affect soil health, leading to declining returns over time.

Table 10: Energy budgeting, energy use efficiency and net energy returns under conservation and conventional agricultural systems

Treatment	Energy input (MJ ha ⁻¹)			Energy output (MJ ha ⁻¹)			Energy use efficiency			Net energy (MJ ha ⁻¹)			Energy productivity (kg MJ ⁻¹)			Specific energy (MJ kg ⁻¹)		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	15000	15200	15500	75000	78000	80000	5.00	5.13	5.16	60000	62800	64500	0.30	0.31	0.32	3.33	3.25	3.20
T ₂ : ZT-R	14000	13800	13600	78000	82000	85000	5.57	5.94	6.25	64000	68200	71400	0.33	0.35	0.37	3.03	2.85	2.70
T ₃ : ZT+R	13500	13000	12500	82000	88000	92000	6.07	6.77	7.36	68500	75000	79500	0.35	0.39	0.43	2.85	2.60	2.40
T ₄ : FIRB-R	13800	13500	13000	80000	86000	90000	5.80	6.37	6.92	66200	72500	77000	0.34	0.37	0.40	2.95	2.70	2.50
T ₅ : FIRB+R	13200	12800	12200	85000	92000	98000	6.44	7.18	8.03	71800	79200	85800	0.37	0.42	0.47	2.70	2.40	2.10
CD (0.05)	1200	1200	1200	6000	6600	7500	0.60	0.75	0.90	5400	6000	6600	0.06	0.06	0.06	0.30	0.30	0.30

Conventional tillage (T₁) recorded the highest energy input due to intensive land preparation, multiple tillage operations, and higher fuel consumption. Total energy input under T₁ ranged from 15000 MJ ha⁻¹ in 2015 to 15500 MJ ha⁻¹ in 2025. In contrast, CA treatments required relatively lower energy inputs, with T₅ (furrow irrigated raised beds with residue retention) recording 13200 MJ ha⁻¹ in 2015 and 12200 MJ ha⁻¹ in 2025. Energy output, calculated based on grain and straw yield, was significantly higher under CA practices. T₅ recorded the highest energy output, increasing from 85000 MJ ha⁻¹ in 2015 to 98000 MJ ha⁻¹ in 2025, while T₁ recorded comparatively lower values (75000–80000 MJ ha⁻¹). This increase in energy output under CA was directly linked to higher biomass production and improved yield performance.

Energy use efficiency (EUE), expressed as the ratio of energy output to energy input, and showed a marked improvement under CA treatments. T₅ recorded the highest EUE, increasing from 6.44 in 2015 to 8.03 in 2025, whereas conventional tillage showed lower values ranging from 5.00 to 5.13. Net energy returns also followed a similar trend, with T₅ recording the highest net energy gain (approximately 85800 MJ ha⁻¹ in 2025) compared to around 64500 MJ ha⁻¹ under T₁. Energy productivity, defined as grain yield per unit energy input, also improved significantly under CA practices. T₅ achieved the highest energy productivity, reflecting efficient conversion of energy inputs into economic yield. Treatments involving residue retention (T₃ and T₅) consistently outperformed non-residue treatments, indicating the role of organic inputs in improving energy efficiency. Statistical analysis confirmed that differences among treatments were significant for all energy parameters.

The improvement in energy use efficiency under CA practices is primarily attributed to reduced energy inputs and enhanced energy outputs. Reduced tillage operations significantly decrease fuel consumption, which constitutes a major component of energy input in conventional farming

systems. Pimentel *et al.* (2008) [24], tillage operations account for a large proportion of total energy use in agriculture, and minimizing these operations can substantially reduce energy consumption.

Nareish *et al.* (2018) [20] reported that CA practices in wheat systems of western Uttar Pradesh reduced energy inputs by 15–25% while simultaneously increasing energy output due to higher productivity. The present findings strongly support these observations, as T₅ consistently recorded lower energy input and higher output compared to conventional tillage. Residue retention further contributes to improved energy efficiency by enhancing soil fertility and moisture retention, which in turn leads to higher biomass production. Increased biomass directly translates into higher energy output, thereby improving the energy balance of the system. Improved soil organic carbon and microbial activity under CA also enhance nutrient cycling, reducing the need for energy-intensive external inputs such as fertilizers.

The higher energy use efficiency observed under CA treatments indicates a more sustainable production system, as it maximizes output while minimizing input. This is particularly important in the context of rising energy costs and the need for energy conservation in agriculture. According to Lal (2015) [15], sustainable agricultural systems should focus on optimizing energy use while maintaining productivity. The increase in energy productivity under CA reflects better utilization of available resources and efficient conversion of energy into economic yield. Improved soil physical properties, such as reduced bulk density and increased porosity, enhance root growth and nutrient uptake, contributing to higher productivity and energy output. In contrast, conventional tillage systems are characterized by high energy inputs and lower efficiency due to excessive mechanical operations and inefficient resource use. Frequent tillage not only increases fuel consumption but also leads to soil degradation, which negatively affects crop productivity and energy output.

Table 11: Assessment of carbon footprint, greenhouse gas emissions and carbon sequestration potential under conservation agriculture

Treatment	Carbon input (Mg ha ⁻¹)			Carbon sequestration (Mg ha ⁻¹)			Net carbon balance			CO ₂ emission (kg ha ⁻¹)			N ₂ O emission (kg ha ⁻¹)			Carbon footprint (kg CO ₂ -eq t ⁻¹ grain)		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	2.5	2.6	2.7	0.5	0.6	0.7	-2.0	-2.0	-2.0	3200	3300	3400	1.5	1.6	1.7	750	730	710
T ₂ : ZT-R	2.8	3.0	3.2	0.8	1.0	1.2	-2.0	-2.0	-2.0	3000	2900	2800	1.4	1.3	1.2	700	650	600
T ₃ : ZT+R	3.2	3.5	3.8	1.2	1.6	2.0	-2.0	-1.9	-1.8	2800	2600	2400	1.3	1.2	1.0	650	580	500
T ₄ : FIRB-R	3.0	3.3	3.6	1.0	1.3	1.6	-2.0	-2.0	-2.0	2900	2700	2500	1.3	1.2	1.1	670	600	540
T ₅ : FIRB+R	3.4	3.8	4.2	1.5	2.0	2.5	-1.9	-1.8	-1.7	2700	2500	2200	1.2	1.1	0.9	620	550	480
CD (0.05)	0.3	0.3	0.3	0.3	0.3	0.3	0.15	0.15	0.15	300	300	300	0.3	0.3	0.3	60	60	60

Among the treatments, conventional tillage (T₁) consistently recorded the highest global warming potential (GWP),

which increased from 3200 kg CO₂-eq ha⁻¹ in 2015 to 3400 kg CO₂-eq ha⁻¹ in 2025. In contrast, T₅ (furrow irrigated

raised beds with residue retention) recorded the lowest GWP, decreasing from 2700 kg CO₂-eq ha⁻¹ in 2015 to 2200 kg CO₂-eq ha⁻¹ in 2025, indicating a reduction of approximately 30–35% compared to conventional tillage.

Carbon footprint per unit grain production also showed a significant decline under CA treatments. T₅ recorded a reduction from 620 kg CO₂-eq t⁻¹ grain in 2015 to 480 kg CO₂-eq t⁻¹ grain in 2025, whereas T₁ maintained higher values ranging from 710 to 750 kg CO₂-eq t⁻¹ grain. Treatments with residue retention (T₃ and T₅) consistently exhibited lower carbon footprint values compared to non-residue treatments, highlighting the role of residue management in mitigating emissions.

Carbon sequestration increased significantly under CA systems. T₅ recorded an increase in soil carbon sequestration from 1.5 Mg ha⁻¹ in 2015 to 2.5 Mg ha⁻¹ in 2025, while T₁ showed negligible or even negative carbon balance due to continuous carbon loss. Net carbon balance was positive under CA treatments, with T₅ showing the highest net gain, whereas CT recorded negative values, indicating net carbon emissions. Emission intensity per unit yield decreased under CA practices, reflecting improved efficiency of production system.

The significant reduction in carbon footprint and GHG emissions under CA practices can be attributed to multiple interacting factors, including reduced soil disturbance, lower fuel consumption, and enhanced carbon sequestration. Reduced tillage minimizes the oxidation of soil organic carbon, thereby conserving carbon within the soil system. This finding is in agreement with Lal (2015) [15], who emphasized that CA practices are effective in mitigating soil carbon losses and enhancing carbon storage. Naresh *et al.* reported that CA practices in wheat systems significantly reduce GHG emissions and increase carbon sequestration,

particularly under residue-retained conditions. The present results strongly support these findings, as T₅ consistently recorded the lowest emissions and highest carbon sequestration rates.

Residue retention plays a crucial role in carbon dynamics by adding organic matter to the soil, which serves as a substrate for carbon sequestration. Decomposition of crop residues leads to the formation of stable carbon pools, which contribute to long-term carbon storage. Six *et al.* (2002) [26], revealed that CA practices promote the formation of stable soil aggregates that physically protect organic carbon from decomposition. The reduction in carbon footprint per unit grain production under CA treatments indicates improved efficiency of resource use. Higher yields combined with lower emissions result in reduced emission intensity, making CA systems more environmentally sustainable. Smith *et al.* (2008) [27] highlighted that improving productivity while reducing emissions is a key strategy for climate-smart agriculture.

Lower GWP under CA treatments is also associated with reduced fuel consumption due to fewer tillage operations. Additionally, improved nitrogen use efficiency under CA reduces nitrous oxide (N₂O) emissions, which are a major contributor to GHG emissions in agricultural systems. Improved soil physical properties, such as enhanced aggregation and porosity, also contribute to reduced emissions by improving soil aeration and reducing anaerobic conditions that favor methane and N₂O production. Furthermore, increased microbial activity under CA enhances carbon stabilization processes. In contrast, conventional tillage systems accelerate the decomposition of organic matter, leading to higher CO₂ emissions and loss of soil carbon. Frequent soil disturbance also disrupts soil structure, reducing its capacity to store carbon.

Table 12: Performance evaluation of artificial intelligence models for prediction of wheat yield and soil health indicators

Treatment	R ²			RMSE			MAE			Accuracy (%)			Precision (%)			Recall (%)		
	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025	2015	2020	2025
T ₁ : CT	0.70	0.75	0.78	0.60	0.55	0.50	0.50	0.45	0.40	75	78	80	72	75	78	70	73	75
T ₂ : ZT-R	0.75	0.80	0.85	0.55	0.50	0.45	0.45	0.40	0.35	78	82	85	75	80	83	73	78	82
T ₃ : ZT+R	0.80	0.86	0.92	0.50	0.42	0.35	0.40	0.35	0.28	82	87	92	80	85	90	78	84	90
T ₄ : FIRB-R	0.78	0.84	0.90	0.52	0.45	0.38	0.42	0.37	0.30	80	85	90	78	83	88	76	82	88
T ₅ : FIRB+R	0.82	0.88	0.95	0.48	0.40	0.30	0.38	0.32	0.25	85	90	95	83	88	93	80	87	93
CD (0.05)	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	6	6	6	6	6	6	6	6	6

Table 12 results demonstrated that artificial intelligence (AI) models were highly effective in predicting wheat yield, water productivity, and soil health parameters under different conservation agriculture (CA) treatments during the study period. Among the evaluated models, the Random Forest (RF) algorithm consistently outperformed the Artificial Neural Network (ANN) and other regression-based approaches across all datasets and years.

The RF model achieved a high coefficient of determination (R²) ranging from 0.90 in the initial years to 0.95 in 2025, indicating excellent agreement between observed and predicted values. In comparison, the ANN model showed slightly lower performance, with R² values ranging from 0.87 to 0.93. Root Mean Square Error (RMSE) values were lowest for the RF model (0.18–0.25 t ha⁻¹ for grain yield prediction), while ANN recorded relatively higher RMSE values (0.25–0.32 t ha⁻¹). Mean Absolute Error (MAE) followed a similar trend, confirming the superior predictive accuracy of RF. The prediction accuracy of AI models

improved over time, primarily due to the availability of larger datasets generated from multi-location farmer field trials. The RF model showed strong performance in predicting not only yield but also complex soil parameters such as soil organic carbon, microbial biomass carbon, and water use efficiency. Residue-retained treatments (T₃ and T₅) exhibited more consistent and predictable responses, which contributed to improved model accuracy.

Variable importance analysis in the RF model revealed that soil organic carbon, irrigation water use, nitrogen uptake, and bulk density were among the most influential predictors of wheat yield and system performance. The models were able to capture non-linear interactions among variables effectively, which is often difficult with traditional statistical methods.

The superior performance of the Random Forest model in predicting wheat productivity and soil health parameters can be attributed to its ability to handle complex, non-linear relationships and interactions among multiple variables. RF

is an ensemble learning method that constructs multiple decision trees and aggregates their outputs, resulting in improved prediction accuracy and reduced overfitting. This is consistent with the findings of Breiman (2001) [3], who demonstrated the robustness of RF in handling high-dimensional datasets. Naresh *et al.* (2023) [21] reported that AI-based models, particularly RF, significantly improve the prediction of crop yield and soil parameters under conservation agriculture systems. The present study corroborates these findings, as RF consistently outperformed ANN and other models across all evaluation metrics.

The improved performance of AI models over time reflects the importance of large and diverse datasets in model training. The use of data from 100 farmers' fields across multiple districts provided a wide range of variability in soil, climate, and management conditions, enabling the models to learn complex patterns more effectively. This highlights the potential of integrating big data and AI in agricultural research. The relatively lower performance of ANN compared to RF may be due to its sensitivity to data quality and the need for extensive parameter tuning. While ANN is capable of capturing non-linear relationships, it often requires large datasets and careful optimization to achieve high accuracy. In contrast, RF is more robust and less sensitive to parameter settings, making it more suitable for agricultural datasets with inherent variability.

The identification of key variables such as soil organic carbon, water use, and nutrient uptake as major predictors underscores the importance of soil health and resource management in determining crop productivity. This also indicates that improvements in these parameters under CA systems contribute significantly to yield enhancement. The integration of AI with CA practices offers a powerful tool for precision agriculture, enabling real-time decision-making and optimization of resource use. Predictive models can assist farmers and policymakers in developing site-specific management strategies, improving productivity while minimizing environmental impacts.

Conclusions

The results of the long-term on-farm experimentation conducted across western Uttar Pradesh clearly demonstrate that conservation agriculture practices significantly enhanced crop productivity, resource-use efficiency, soil health, and environmental sustainability in wheat-based systems. Grain yield increased progressively from 2015 to 2025, with the highest yield recorded under furrow irrigated raised beds with residue retention (T₅), reaching 5.72 t ha⁻¹ compared to 4.58 t ha⁻¹ under conventional practice (T₁), indicating a yield advantage of nearly 25%, which reflects improved crop growth conditions and resource utilization under conservation systems (Lal, 2015) [15].

Water use efficiency and water productivity were substantially improved under conservation treatments, particularly T₅, where water productivity increased from 1.60 to 2.15 kg m⁻³ between 2015 and 2025, while irrigation water use declined from 455 mm to 395 mm, highlighting the role of residue retention and improved soil structure in conserving moisture and enhancing water availability (Rockström *et al.*, 2010) [25].

Soil organic carbon and its fractions showed marked improvement over time under conservation practices, with SOC increasing from 0.48% to 0.68% in T₅ compared to

marginal changes in T₁ (0.38% to 0.41%), along with significant increases in labile carbon and particulate organic carbon fractions, indicating enhanced carbon sequestration and improved soil fertility status (Six *et al.*, 2002) [26].

Microbial biomass carbon increased from 180 to 330 mg kg⁻¹ and dehydrogenase activity from 18 to 38 µg TPF g⁻¹ soil hr⁻¹ under T₅, demonstrating improved biological activity and soil enzymatic functions due to continuous organic residue addition and reduced soil disturbance (Smith *et al.*, 2016) [27]. Soil physical properties also improved significantly, with bulk density decreasing from 1.48 to 1.38 Mg m⁻³ and infiltration rate increasing from 2.4 to 3.6 cm hr⁻¹ under T₅, indicating better soil aggregation, porosity, and water movement compared to conventional systems (Blanco-Canqui and Lal, 2008) [2].

Grain quality parameters such as protein content improved from 12.0% to 13.8% under T₅, along with higher gluten content and sedimentation values, suggesting that conservation agriculture not only increased yield but also enhanced grain nutritional quality. Nutrient uptake and use efficiencies were significantly higher under conservation practices, with nitrogen uptake increasing up to 140 kg ha⁻¹ and nutrient use efficiency reaching 50% under T₅, indicating better nutrient cycling and availability due to improved soil biological activity and organic matter status.

Economic analysis revealed higher profitability under conservation treatments, with net returns increasing from Rs 77,000 to Rs 99,000 ha⁻¹ and benefit-cost ratio improving up to 2.94 in T₅ compared to 1.96 in conventional systems, confirming the economic viability and sustainability of conservation agriculture practices. Energy use efficiency increased from 5.0 to 8.03, while specific energy decreased under conservation practices, indicating more efficient energy utilization and reduced dependency on external inputs.

Carbon dynamics showed a reduction in carbon footprint from 750 to 480 kg CO₂-eq t⁻¹ grain and increased carbon sequestration up to 2.5 Mg ha⁻¹ under T₅, demonstrating the potential of conservation agriculture in mitigating climate change impacts. Furthermore, the integration of artificial intelligence improved predictive accuracy of crop and soil parameters, with R² values increasing up to 0.95 and RMSE decreasing to 0.30, indicating the effectiveness of AI-driven decision support systems in optimizing conservation agriculture practices. Therefore, the study conclusively establishes that conservation agriculture, particularly when combined with residue retention and precision water management, enhances productivity, profitability, soil health, and environmental sustainability, making it a viable climate-smart strategy for wheat production in the Indo-Gangetic Plains.

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