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Arid irrigated winter wheat and soybean cropping under conservation tillage systems

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This research aimed to determine the effects of conservation tillage practices on the soil quality parameters and productivity of winter wheat (WW) followed by soybean (SB) in a conventionally irrigated arid environment. Field experiments were conducted in 2020–2023 in a split-plot design with the following four land management practices: conventional tillage (CT: moldboard plow + harrow), RT1 (chisel + harrow), RT2 (disk + harrow), and NT (no-till – without tillage). After three experimental cycles, the soil humus content increased by 10, 12, and 15% ($p < 0.05$) in the CT, RT1, and RT2 plots, respectively, while the highest soil humus was detected in the NT plot. Soil bulk density decreased from 1.6 g/cm^3 to 1.33, 1.42, and 1.34 g/cm^3 ($p < 0.05$) in the CT, RT1, and RT2 plots, respectively. A significant increase was found at the NT plot in terms of soil quality indicators such as total N and P, available N–NO$_3$, P$_2$O$_5$, and K$_2$O. The application of NT increased the yield components of WW and SB by 20 and 12%, respectively, compared to CT. This study showed that the highest WW (6.84 Mg ha^{-1}) and SB (2.12 Mg ha^{-1}) grain yields were achieved in the NT plot, most likely due to enhanced moisture and nutrient conservation, facilitated by the high amount of crop residues on the soil surface. The implemented NT method combined with the legume-based cropping system appears to be a more sustainable and environmentally friendly land management system to achieve a favorable soil environment that generates higher crop yield in the arid ecosystem.

KEYWORDS
crop, yield, conventional tillage, reduced tillage, no-till, soybean, soil quality, winter wheat

1 Introduction

Tillage is a crucial agricultural soil preparation process that affects a wide range of soil properties. The long-term effects of applied tillage practices on soil health are complex, site-specific, and influenced by the associated crop species (Zapata et al., 2021). The conventional (crop–fallow) tillage system is still predominant in Uzbekistan, contributing to soil organic matter depletion due to excessive deep plowing and frequent tillage practices. Risks related to land degradation and desertification have become apparent in the majority of irrigated land in Uzbekistan, posing a significant barrier to ensuring food security and reducing rural poverty (Nurbekov et al., 2024). In contrast, identifying the positive impacts of rational land management is essential for protecting natural resources and rejuvenating vulnerable dryland environments.

Implementing conservation tillage practices can promote various ecosystem services that will mitigate the growing challenges of food security, poverty, and climate change impacts. These agricultural practices in arid regions should focus on the use of *in situ* soil moisture conservation systems, such as minimum tillage, to maximize labor, money, time, and energy efficiency. Conservation tillage comprises a range of reduced and zero tillage methods that leave at least 30% of the crop residue on the soil surface (Islam et al., 2021). Cover crop residues are deposited on the soil surface, forming a mulch layer and maintaining soil protection against wind and water erosion. This land management practice has the capability to improve ecosystem services, e.g., enhancing soil structure and water retention ability by increasing its organic carbon content and reducing topsoil erosion. In addition, conservation tillage has a significant impact on the soil's hydrologic qualities and temperature (Hirsch et al., 2017), stabilizing water permeability, moisture retention, and nutrient stocks (Shen et al., 2018), and decreasing runoff and compaction (Piccoli et al., 2017). However, site- and context-specific functions play an important role in the implementation of any tillage system (Toth et al., 2024).

Winter wheat (*Triticum aestivum* L.) is well adapted to limited water dry environments, standing as a cornerstone in the food supply of Uzbekistan. The area under this important cereal increased more than fivefold, from 0.25 million ha in 1991 to 1.26 million ha in 2024, with at least a twofold grain yield increase (5 tons/ha) during this period (FAOSTAT, 2022). This achievement has been very important for further strengthening the country's food security.

Soybean (*Glycine max* L. Merr.) as a follow-up crop after WW has a great potential to reduce soil erosion and degradation; at the same time, it can improve soil quality by enhancing soil organic matter. This crop also serves as a cover crop in irrigated lands, decreasing soil moisture loss, topsoil heating, and secondary salinization. In addition, soybean maintains field microclimate and phytosanitary conditions and provides nitrogen (N) via biological N fixation and soil microbiological processes. Despite these advantages, the area occupied by this crop only reaches 12,385 ha, with an average yield of 2.8 t/ha (FAOSTAT, 2022).

However, it is crucial to acknowledge that the short- and long-term effects of minimum tillage methods compared to conventional tillage on soil conditions in Uzbekistan are not well documented. WW is the main crop in Uzbekistan, planted in the middle of autumn and harvested in the early summer of the following year. Typically, the land following WW remains unused during the summer in this arid region due to water scarcity, despite having enough active growth period for a second crop (Nurbekov et al., 2023). Therefore, assessing the impact of conservation tillage in combination with cereal–legume cropping patterns is crucial for finding science-based innovative solutions under the soil salinity and drought risk agroecosystem of the region.

An essential step in the widespread adoption of conservation-oriented agricultural practices, such as RT or NT, should be associated with maintaining soil health, enhancing natural soil fertility, and preventing soil compaction and erosion. Soil fertility remains a key indicator of any implemented agrotechnology, while the dynamics of soil organic matter (SOM) are affected by tillage, crop rotation, moisture retention, soil texture, and plant residue content.

The study hypothesis focused on the idea that soil management systems based on minimum tillage could improve soil nutrient budgets, stabilize or boost crop yields, and reduce production costs, offering a practical solution for transitioning from conventional to conservation tillage. Thus, the research aimed to define the best tillage practice by assessing relative crop yields along with a set of soil biological, chemical, and physical properties.

2 Materials and methods

2.1 Climate and soil conditions

The experiment was carried out at the experimental field of the Tashkent State Agrarian University, located in the northeast of Uzbekistan (41°37′N; 69°33′E). The climate in this region is characterized as sharp continental, with dry, hot summers and relatively mild winters. The annual precipitation is 170–260 mm, whereas the evaporative potential reaches 1,600–1,800 mm. The highest air temperature is observed in July (+42°C), while the lowest is expected in January, up to −30°C. The air moisture ranges from 51 to −58%. The sum of positive temperatures (above +10°C) during the vegetation period is approximately 2,200–2,600°C. The average length of the frost-free period is 250–265 days. During the experiment years, precipitation and air temperatures were typical for the area. The total precipitation for 2020, 2021, 2022, and 2023 was 220, 236.5, 156.9, and 193.5 mm, respectively (Figure 1), with only 10–15% of this rainfall occurring during the vegetation period. This makes irrigation a prerequisite for crop production in this region.

2.2 Soil parameters and sampling

The soil texture is clay loam, which is characterized by low humus content ranging from approximately 1.2–1.5%. This low organic matter content is insufficient for producing high crop yields unless special land management procedures are implemented. Initial soil analysis showed that the presence of total and available forms of N, P, and K within soil profiles differed significantly. Total forms of N were 0.026–0.076%, phosphorus 0.085–0.217%, and potassium 0.71–1.66% at the 0–20 cm soil depth. Carbonate CO_2 fluctuated at approximately 7.43–7.60% within soil profiles, while gypsum SO_4 was 0.099–0.156%.

Three replicated soil samples from each plot were taken using an auger at depths of 0–20 and 20–40 cm before setting up and at the end of the experiment. A total of 72 soil samples (4 land management methods × 3 replicated plots × 2 soil depths × 3 soil samples from each plot) were collected. After air-drying at room temperature of 25°C for 14 days, these samples were sieved through a 2-mm mesh. Then, these collected soil samples were assigned for chemical and physical analysis as per the standard methods developed by Ryan et al. (2001) and NIAST (2000). A conductivity meter was used to measure soil pH and EC parameters. Total N was assessed using the dry combustion method. The ascorbic acid method was employed to analyze spectrophotometrically total P in acid digestate (Murphy and Riley, 1962). K was determined using the flame photometry procedure in the diluted acid digestate.

Root samples were taken by collecting 5.25 cm diameter cores to a depth of 40 cm at 20 cm, 40 cm, and 25 cm perpendicular to the crop row. Soil cores were cut into 0–5, 5–10, 10–20, 20–30, 30–40, and 40–60 cm layers. After washing and separating the soil and roots, root traits (biomass, length, surface, and diameter, and the proportions of

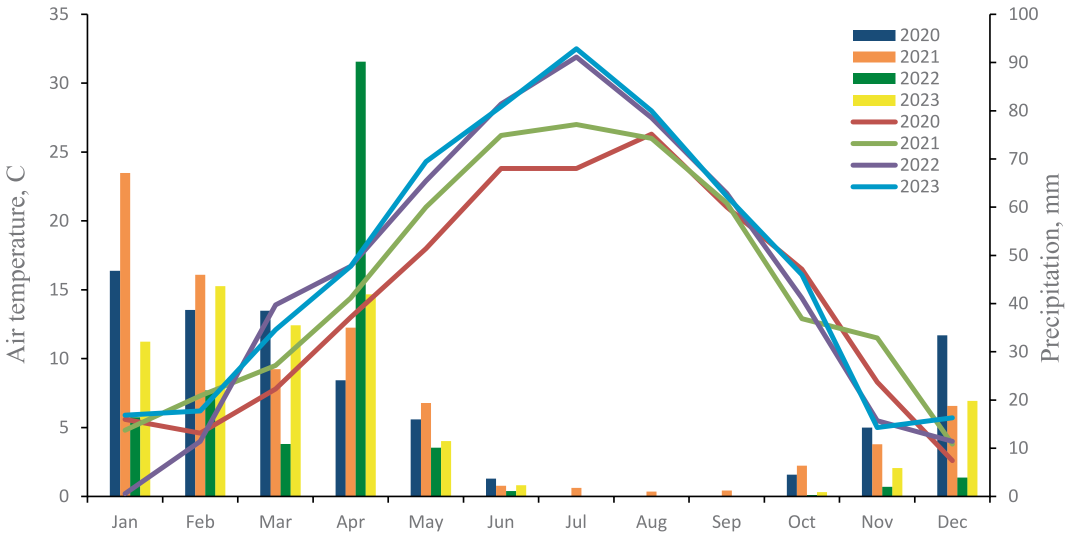

FIGURE 1
Weather data of air temperature (in curves) and rainfall (in columns) of the study area, Tashkent State Agrarian University, Tashkent, Uzbekistan (2020–2023 growth years and long-term data). Source: Meteorological Station of Tashkent Region, Tashkent, Uzbekistan.

primary, secondary, and tertiary roots) were quantified using the WinRHIZO software.

Crop yield was determined from randomly chosen points in each plot, and the values were then converted to megagrams (Mg) per hectare.

2.3 Experiment design and agrotechnique measures

This trial site experienced conventional tillage over a long period before the experiment was established. The soil management systems used in this study were conventional tillage (CT), reduced tillage 1 (RT1), reduced tillage 2 (RT2), and no-tillage (NT) (Table 1). Identical plot sizes were maintained for the tested four tillage treatments × crop species. The main factor was the four tillage treatments that were evaluated in the WW-SB cropping pattern. Three replications and a split-plot design were used to set up the experiment. Each plot measured $30\ \text{m} \times 5\ \text{m} = 150\ \text{m}^2$. Foliar nutrition at a rate of 20 kg N/ha was applied to all WW plots in the early spring. All agronomic activities were arranged similarly, i.e., fertilizers and irrigation norms were supplied in equal amounts to all plots. The crop rotation included winter wheat (cv. Brigada) and soybean (cv. Orzu). In the middle of October, WW was sown at a seed rate of 100 kg/ha, while it was harvested in the middle of June. After that, SB seeds were planted at a rate of 60 kg/ha and harvested in October. The cropping cycle was sustained with WW followed by SB.

During the mechanical sowing of wheat, a uniform application of 60 kg P_2O_5 + 40 kg K_2O per ha was applied as a basal fertilizer to every plot. Two equal splits of 150 kg N/ha were applied at 37 and 84 days after sowing (DAS). Conventional flood irrigation with a norm of 800 m^3 per ha was applied for WW in October prior to seed planting and in May during the flowering phase, whereas for SB in July before seed sowing.

2.4 Statistical analysis

The assessed parameters of the soil and crop samples were measured three times to calculate an average value with appropriate degrees of certainty, to estimate errors, and to enable data testing for statistical systems. All significant differences, unless otherwise specified, were reported at $p < 0.05$. Collected data were organized in Microsoft Excel 2013, and the experimental data were statistically analyzed with the CropStat (ANOVA) program (2015).

3 Results

3.1 Crop yield

The tested conservation tillage treatments significantly affected the crop yield values of both crops, namely, WW and SB (Table 2). The grain accumulation of the crops exhibited an increasing trend under the conservation tillage methods. RT1 and RT2 treatments in this three-cycle experiment exhibited higher crop yield, whereas NT generated the highest WW grain yield. In the 2020–2021 vegetation cycle, crop productivity progressed in the following sequence: CT < RT1 < RT2 < NT for both crops. The highest WW yield was recorded under NT (6.54 Mg/ha), followed by RT2 (6.02 Mg/ha) and RT1 (5.41 Mg/ha), which showed 24.8, 14.9, and 3.4% higher values, respectively, compared to CT. SB also experienced the same progression trend with 30.8, 11.5, and 6.4% increases in the NT, RT2, and RT1 plots than that of the CT value. The increasing trend of grain yield for both crops from CT to RT1 – RT2 – NT was also observed for the 2021–2022 and 2022–2023 vegetation cycles.

The results of the analysis of variance indicated significant differences in WW and SB yields among years, whereas a non-significant year × yield interaction was observed between the first and second cycles in all systems. However, at the third vegetation cycle, a statistically significant difference was observed

TABLE 1 Experiment design.

Treatments	For winter wheat	For soybean
CT	Conventional tillage – moldboard plowing (30 cm depth), disking + harrowing + seed planted with disk openers and a precise seed furrow-closing mechanism	Conventional tillage – moldboard plowing (30 cm depth), disking + harrowing + seed planted with disk openers and a precise seed furrow-closing mechanism
RT1	Cultivator (15 cm depth) to remove cotton stocks + chiseling + harrowing + seed planted with disk openers and a precise seed furrow-closing mechanism	Chiseling + harrowing + seed planted with disk openers and a precise seed furrow-closing mechanism
RT2	Cultivator (15 cm depth) to remove cotton stocks + disking + harrowing + seed planted with disk openers and a precise seed furrow-closing mechanism	Disking + harrowing + seed planted with disc openers and a precise seed furrow-closing mechanism
NT	No-till – seed planted with disk openers and precise seed furrow-closing equipment	No-till – seed planted with disk openers and precise seed furrow-closing equipment

TABLE 2 Grain yield of WW and SB (Mg/ha).

Tillage systems	Year of study						Treatment mean	
	2020–2021		2021–2022		2022–2023			
	WW	SB	WW	SB	WW	SB	WW	SB
CT	5.24c	1.56c	5.41c	1.61c	5.48c	1.70c	5.38c	1.62c
RT1	5.42c	1.66b	5.54c	1.73b	5.71c	1.79b	5.56c	1.73b
RT2	6.02b	1.74b	6.23b	1.87b	6.30b	1.87b	6.18b	1.83b
NT	6.54a	2.04a	6.88a	2.12a	7.09a	2.21a	6.84a	2.12a
Year mean	5.81B	1.75B	6.02A	1.83	6.15A	1.89A		
$\text{LSD}_{0.05}$								
Tillage	0.35	0.18	0.39	0.17	0.42	0.16	0.34	1.5
Year	–	–	–	–	–	–	0.6	–
Tillage × year	–	–	–	–	–	–	0.4	–

Means in each column followed by the same letter are significantly different at a *p*-value of >0.05.

for RT1, RT2, and NT, except for CT. The grain yield of WW increased by 8.4% under NT, reaching a significant point at the 2022–2023 vegetation cycle as compared to the 2020–2021 period, while, in the case of RT2, RT1, and CT, these WW values were 4.7, 5.4, and 4.6% higher, respectively, between the above-compared cycles.

A similar trend of increasing grain yield was also observed for SB. There was a significant difference in the cropping cycle × grain yield interactions between the 2020–2021 and 2022–2023 vegetation seasons of the SB data. In this period, the SB grain yield increased by 8.3, 7.5, 7.8, and 5.1% under NT, RT2, RT1, and CT, respectively.

NT with total residue management and WW-SB cropping cycle produced significantly more grain than the other tillage systems.

There was also a statistically significant difference in the tillage treatments on WW grain quality when averaged over the growing cycles (Table 3). Protein content in WW grain was higher by 5.3% when NT was compared to CT. These indices did not have a significant level in RT1 and RT2 compared to CT for WW, even showing higher levels. Similarly, the gluten content showed an increasing trend CT < RT1 < RT2 < NT, exhibiting a significant level at the NT parameter.

TABLE 3 Grain quality parameters of the crops (averaged across the growth seasons).

Treatments	Winter wheat		Soybean	
	Protein, %	Gluten, %	Protein, %	Oil content, %
CT	13.61b	26.4b	35.6b	24.1b
RT1	13.81ab	27.6ab	35.8ab	24.3ab
RT2	13.92ab	26.8ab	35.9ab	24.7ab
NT	14.33a	29.5a	36.6a	25.8a
Year mean	13.92	27.6	35.98	24.7
$\text{LSD}_{0.05}$				
Tillage	0.61	2.4	0.78	0.89

Means in each column followed by the same letter are significantly different at a *p*-value of >0.05.

Similarly, SB grain quality parameters, such as protein and oil content, were more pronounced in the NT treatment. The highest SB oil and protein contents were observed in the NT practice, increasing these values by an average of 2.8 and 7.1% compared to the CT group. Although not statistically different, SB protein and oil contents were enhanced in the RT1 and RT2 treatments.

3.2 Soil characteristics

Soil physical parameters were significantly different between the tillage treatments for both crops ($p < 0.05$) after the three vegetation cycles (Table 4). The NT plot had 10.5–14.2% lower soil bulk density compared to CT at 0–20 and 20–40 soil profiles, showing a positive attitude toward improving soil quality indices. An increased soil structure in the NT plots in terms of total porosity and electrical conductivity indices was substantial. Soil electrical conductivity significantly differed among the tillage practices, demonstrating the advantages of conservation tillage on soil salinity problems. Total soil porosity was 49.42% for NT, 46.77% for RT1 and RT2, and 43.07% for CT at the 0–20 cm soil depth.

Compared to CT, these soil physical parameters were also significantly improved in the RT1 and RT2 treatments, showing benefits for crop production. The conservation tillage systems, especially NT, also fostered the improvement of other important soil physical characteristics, such as aggregate stability, soil compaction, and water holding capacity, in the upper 0–20 cm soil layer (data not shown).

The tested tillage treatments had a significant impact on the soil chemical parameters (Table 5). The soil humus content in response to tillage treatments was significantly different at a p-value of <0.05. The largest improvement was observed in the NT plot, where the soil humus content reached 1.19%, compared to 1.17% for RT2, 1.04% for RT1, and 0.91% for CT at the 0–20 cm depth.

The NT system enhanced N, P, and K contents by 31.2, 14.8, and 19.2%, respectively, in the 0–20 cm depth, showing a positive correlation with the humus content. The conservation tillage system also affected N, P, and K values in the 20–40 cm soil profile, although these differences were not statistically significant. Similarly, a significant increase was noted only between the CT and NT plots in the 20–40 cm soil depth, with 0.89 and 1.0% humus content, respectively.

The same trend was also observed for the available forms of nutrients such as N–NO_3, P_2O_5, and K_2O. The highest N–NO_3, P_2O_5, and K_2O levels were recorded for NT in the 0–20 cm soil profile and remained stable over time in the NT plot. In contrast, these parameters did not change significantly in the 20–40 cm soil depth in all plots.

Generally, NT in association with legume-based crop rotation (WW-SB) and residue management was found to have positive effects on soil quality parameters in arid agricultural environments.

3.3 Crop residues and soil moisture

Crop residue retention was significantly affected by both reduced and conservation tillage systems (Table 6). Phyto and root residue exhibited significantly higher values in the NT plot for both crops.

Total WW residue increased by 87.6% in NT, 57.8% in RT2, and 24.3% in RT1 compared to the CT practice. Despite the relatively low total residue retention under SB, the same trend was observed. The highest SB residue was retrieved under NT, followed by RT2 and RT1 plots with 41.4, 15.1, and 13.5% higher values, respectively, than that of the CT plot.

The higher crop yield in the NT plot could be related to the retention of total residue on the soil surface after harvesting. Consequently, the enhanced crop residues on the soil surface under the conservation system positively affected crop productivity, displaying its linear relationships with soil health.

TABLE 4 Soil physical properties of the investigated tillage systems at the end of the experiment.

Treatments	Soil profiles, cm	Soil bulk density, g/cm^3	Electrical conductivity, ECe (dS/m)	Total porosity, %
At the beginning of the experiment				
	0–20	1.36a	3.3a	45.47b
	20–40	1.51a	3.2a	42.17c
At the end of the experiment				
CT	0–20	1.37a	3.4a	43.07c
RT1	0–20	1.30b	2.9b	46.77b
RT2	0–20	1.27c	2.8b	46.77b
NT	0–20	1.24c	3.0b	49.42a
CT	20–40	1.53a	3.2a	40.67c
RT1	20–40	1.44b	2.7b	45.65b
RT2	20–40	1.41b	2.5b	45.65b
NT	20–40	1.34b	2.7b	48.46a
Year mean		1.36	2.90	45.81
$LSD_{0.05}$				
Tillage		0.62	0.35	2.14

Means in each column followed by the same letter are significantly different at a p-value of >0.05.

TABLE 5 Soil chemical analysis.

Treatments	Soil depth	Humus	Total, %			Available, mg/kg		
			N	P	K	$N{-}NO_3$	P_2O_5	K_2O
At the beginning of the experiment								
	0–20	1.1	0.056	0.131	0.47	25.3	8.28	305
	20–40	0.8	0.041	0.167	0.53	21.0	21.78	144
At the end of the experiment								
CT	0–20	0.91c	0.064c	0.130c	0.47b	21.3d	17.32b	145a
RT1	0–20	1.04b	0.071b	0.131c	0.53ab	27.2c	18.28b	144a
RT2	0–20	1.17a	0.073b	0.145a	0.54ab	30.3b	19.75b	140b
NT	0–20	1.19a	0.084a	0.155a	0.56a	44.2a	21.78a	147a
CT	20–40	0.89b	0.037a	0.137a	0.46a	26.0b	13.6b	142b
RT1	20–40	0.95a	0.038a	0.140a	0.47a	28.1a	14.0a	146b
RT2	20–40	0.98a	0.038a	0.136a	0.49a	29.0a	15.8a	144b
NT	20–40	1.00a	0.040a	0.139a	0.47a	29.1a	15.8a	158a
Year mean		0.056	0.139	0.50	29.40	17.041	146	0.056
LSD$_{0.05}$								
Tillage		0.15	0.012	0.011	0.009	2.65	2.43	9.7

Means in each column followed by the same letter are significantly different at a *p*-value of >0.05.

TABLE 6 Crop residues under different tillage practices (averaged across the growth seasons).

Treatments	Winter wheat				Soybean			
	Phyto residues, Mg/ha	Root residues, Mg/ha		Total residues, Mg/ha	Phyto residues, Mg/ha	Root residues, ton/ha		Total residues, Mg/ha
		0–20 cm	20–40 cm			0–20 cm	20–40 cm	
CT	13.5d	8.9d	1.1b	23.5d	5.6c	4.5c	3.2c	13.3c
RT1	17.9c	14.2c	2.1ab	29.2c	5.9b	5.6b	3.6b	15.1b
RT2	20.4b	16.2b	2.5ab	37.1b	6.0b	5.7b	3.6b	15.3b
NT	22.4a	19.0a	2.7a	44.1a	6.7a	6.1a	4.0a	18.8a
Year mean	18.6	14.6	2.1	33.5	6.1	5.5	3.6	15.6
LSD$_{0.05}$								
Tillage	1.8	2.0	0.9	3.4	0.44	0.32	0.24	2.21

Means in each column followed by the same letter are significantly different at a *p*-value of >0.05.

TABLE 7 Amount of macro-elements (N, P, and K) in the WW and SB residues (averaged across the growth seasons).

Treatments	Winter wheat			Soybean		
	N, %	P, %	K, %	N, %	P, %	K, %
CT	0.47c	0.209c	1.32c	2.53c	0.612c	1.78c
RT1	0.51b	0.224b	1.41b	2.66b	0.677b	1.91b
RT2	0.52b	0.231a	1.44b	2.73b	0.692b	2.04b
NT	0.58a	0.233a	1.56a	2.89a	0.743a	2.26a
Year mean	0.52	0.224	1.43	2.70	0.681	2.00
LSD$_{0.05}$						
Tillage	0.34	0.011	0.12	0.13	0.065	0.17

Means in each column followed by the same letter are significantly different at a *p*-value of >0.05.

The application of the NT practice improved the quality indicators, i.e., NPK concentrations in crop residues. The N, P, and K concentrations increased by 22.8, 11.5, and 18.2% in the WW residue and 14.2, 21.4, and 26.9% in the SB residues in the NT plot compared to the CT values (Table 7).

The NPK parameters were not significantly different between RT2 and RT1 for both crops. However, the NPK values in WW residues were higher by 10.6, 11.5, and 18.2%, respectively, under RT2 and 8.5, 7.2, and 6.8% higher under RT1 compared to the CT parameters.

Similarly, N, P, and K concentrations in soybean residues increased by 14.2, 21.4, and 26.9% under NT than that of the CT values. These N, P, and K values were 7.9, 13.1, and 14.4% higher under RT2 and 5.1, 10.6, and 7.3% higher under RT1 as compared to the CT group.

The soil moisture content in the NT plot was invariably higher than that of the CT plot (Figure 2). A polynomial regression also showed a more significant effect of soil moisture during the growth period for NT ($R^2 = 0.6089$, $p < 0.005$) than for the other treatments.

Increased moisture availability in the NT plot contributed to crop productive growth. This parameter was influenced by irrigation accordingly. During the hot season—June, July, and August—soil

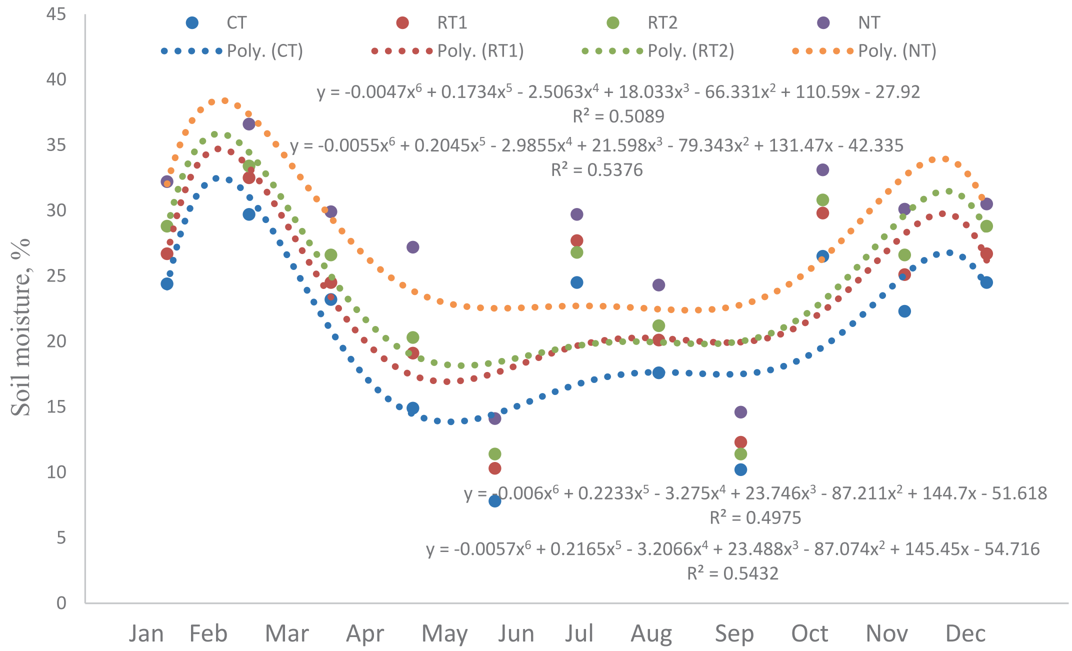

FIGURE 2
Soil moisture content (averaged across the growth seasons).

moisture was 14.1, 29.7, and 24.3% higher in the NT plot compared to the CT plot.

Taken together, the synergy of NT × legume-based crop rotation × residue management had a positive effect on soil moisture retention parameters.

4 Discussion

4.1 Tillage, crop rotation, and yield

Land degradation has been progressing in the region for decades, causing more unfavorable changes to the ecosystem that urgently require soil protection and conservation measures. Research and restoration efforts in land management are an efficient strategy for this region, transforming the agricultural sector into a productive and functional ecosystem (Rustamova et al., 2023). A strong driver of food security and agro-environmental sustainability in response to the long-term effects of conservation tillage practices was prioritized in this study.

This study showed that NT is an effective technique for promoting crop productivity and improving soil fertility indicators in arid regions. The crop yield of both WW and SB was higher under NT than those under RT or CT. The use of conservation tillage leads to soil quality improvement and reduced energy consumption by combining balanced plant residue management with less soil tilling. In agreement with this study, a review by Du et al. (2022) discussed the effects of field management measures on the soil environment and highlighted the importance of straw mulching and reduced tillage practices in arid regions which significantly improved soil biological functions, water use efficiency, and crop yield. In addition to the environmentally friendly functions, this farming technique maintains good ecosystem functions in harsh settings, having significant positive effects on soil water content and temperature parameters (Giller et al., 2009). Similarly, the use of wheat straw mulching lowered soil temperature when the ambient temperature was high and vice versa (Liu et al., 2021).

The lack of organic return to the soil is causing soil structure deterioration under the existing cotton-WW crop cycles under conventional tillage (Khaitov et al., 2024). To rescue the situation, implementing RT was found to have higher levels of decomposed crop residues in the soil. Several studies have shown that NT combined with straw mulching can enhance the diversity of soil microorganisms, microbial biomass, and their activity (Chen et al., 2021; Hydbom et al., 2017; Fatemi et al., 2016). As indicated by Muñoz et al. (2022), soil enzymes play an active role in the transformation of soil nutrients into available forms for plant uptake.

According to our research, NT produced the biggest improvements in soil quality in the upper soil layer, particularly through minimal soil disturbance (direct seeding) and the maintenance of a dense surface cover. In contrast, lower crop yield under CT could be explained by generated soil compaction, low soil water permeability, and poor root development (Tracy et al., 2011). As indicated by Sharma et al. (2019), increased soil tillage activity in arable crops—particularly moldboard deep plowing—has typically led to decreases in soil C pool size, seriously damaging soil fertility indicators. Reduced tillage techniques may also be able to raise or stabilize the amount of carbon (C) in soil layers under arable crops that had previously been plowed. Crop residues incorporated into the soil will increase organic matter availability to microorganisms, thereby increasing the carbon sequestration process (Sharma et al., 2021). Therefore, it makes sense to use less tillage as an essential approach to improve soil C sequestration and lower net CO_2 emissions in agricultural fields; however, these outcomes may vary depending on the surrounding circumstances.

The increase in crop yield under the conservation tillage systems is associated with selecting appropriate crop rotations that take advantage of the ability of legumes to fix nitrogen and maximize N cycling through management (Ginakes and Grossman, 2021). In addition to the decreased yield in CT plots, this practice is considered unprofitable for crop producers in terms of time consumption, energy inefficiency, and labor intensity. Cover crop-based reduced tillage refers to a group of techniques that deliberately incorporate cover crops into a rotation as a cash crop to minimize soil disturbance (Vincent-Caboud et al., 2019).

During the three-cycle study, the grain yield of WW and SB also increased with improving soil environments. Analysis of variance exhibited significant differences in WW and SB yields in response to the tested tillage treatments × growing cycle interactions. Overall, the studied crop performance indices, i.e., grain yields of WW and SB, were ranked as follows: NT > RT2 > RT1 > CT. The effectiveness of these techniques with respect to increasing soil organic matter, reducing surface water evaporation, and boosting soil microbial activity was likely influenced by the increased straw mulching retention on the soil surface. This study in the arid region exhibited that the effect of conservation tillage, particularly NT and RT, is of great significance for agricultural production.

4.2 Soil water storage

An application of NT in combination with legume-based crop rotation and straw mulch management increases yields and water use efficiency and further enhances soil structure in areas with annual precipitation below 250 mm (Hemmat and Eskandari, 2006). It appears that NT technology would perfectly fit the dryland conditions of Uzbekistan. As shown in Figure 1, the weather conditions during the trial years (2020–2023) in the Tashkent region included total rainfall of 220, 236.5, 156.9, and 193.5 mm, in 2020, 2021, 2022, and 2023, respectively.

The amount of rainfall during the experimental years was typical for the region, except for 2022, which was characterized by less rainfall (156.9 mm). Therefore, the crops may be exposed to water stress due to insufficient rainfall. However, precipitation reached 90.2 mm in April, reducing water stress, which also contributed to the accumulation of moisture in the soil and the vigorous growth of WW. SB was sown in late June, and because of the absence of precipitation during this period, irrigation was essential. No rainfall in July and August made it a decisive factor to irrigate for SB. There was only 1.2–4.5 mm of precipitation in October, which was not enough for seed germination of WW.

The temperature during this period was good enough for seed germination, with an average rate of 12–16°C. The winter of 2022 was accompanied by extraordinarily cold weather, but sufficient snowfall brought moisture accumulation to the soil. A long period of relatively cool weather in the spring and April precipitations (41.9 mm) also contributed to the accumulation of moisture in the soil.

The presence of crop residues on the soil surface is the primary reason for the high soil moisture associated with NT systems (Li et al., 2018; Nurbekov et al., 2023). According to recent discoveries, NT management of wheat residues increased the amount of water in the soil by 29 mm in continuous wheat, 15 mm in wheat–fallow, and 22 mm in wheat–sorghum–fallow for the following crop. These authors came to the conclusion that NT management should be used in dryland farming, where yearly rainfall is less than 200 mm, to increase the soil water content and intensify the frequency of cropping.

In this study, increased soil moisture under NT was responsible for the high grain yields of both WW and SB, which were significantly greater than the other systems. In agreement with this outcome, grain yield under NT increased with the increase in soil moisture conditions during the growing season (Yang et al., 2018). Most likely, good soil pre-moisture and field environment allowed plants to form a well-developed root system and tolerate summer drought.

The practical advancement of conservation tillage has emerged as a promising solution for sustainable agriculture, leading to benefits to crop production and soil properties under harsh arid environments. Above all, NT with mulching significantly contributed to high soil moisture retention in the dryland ecosystem, which served as a responsible factor for enhanced crop productivity.

4.3 Soil health

The soil environment should be manipulated suitably for sustaining crop production, whereas maintaining the balance of these systems is of paramount importance (Karunakaran and Behera, 2015). This experiment showed that significant impacts may not be achieved by a short-term implementation of conservation tillage practices. In agreement with this point, Nurbekov et al. (2016) emphasized that a 1-year rotation was not effective when the soil was too depleted. The effects of CT practices may vary consistently depending on the soil–climatic variations of agricultural ecosystems. Soil organic matter is considered the most significant indicator of soil quality. Based on the amount of soil organic matter, modifications materialize in the dynamics of soil properties, i.e., physical, chemical, and biological means. These soil characteristics reflect the effects of land management and vegetation dynamics, rejuvenating the biological function of the soil.

This long-term experiment revealed that soil organic matter content significantly increased under NT practice. The productivity of both crops also increased with the increasing soil fertility. These positive effects may have been caused by the accumulation of crop residues on the soil surface and their incorporation into the soil. NT also promotes the buildup of soil organic carbon (SOC) and increases soil porosity and microbial biomass. More importantly, soil electrical conductivity was significantly reduced due to the applied conservation tillage practices, especially under NT (Table 4), showing the benefits of conservation tillage to combat soil salinity problems in the region.

Conservation tillage should be used in conjunction with other management techniques because it cannot completely regulate all biological processes occurring in the soil. Integrating legume-based cropping patterns into the conservation tillage system is likely to have played an important role in the higher grain yield observed in the NT plot. A positive impact was reached through this integrated approach, causing long-term sustainable benefits from the CT land management practice. These results were also supported by a group of researchers who declared that legume-based crop rotation under NT had a positive impact on soil restoration by increasing nutrient stocks and soil biological dynamics (Abdiev et al., 2019). It is well known that SB as a member of the legume family is capable of generating N through the N fixation process. A successive crop (WW) can utilize the N left in the soil by SB. This result is consistent with previous studies (Khaitov et al., 2024), which explained that various legumes can be effective in a crop rotation plan to increase agricultural productivity under conservation tillage systems and maintain an ecosystem balance (Li et al., 2018).

There was a positive interaction of tillage x rotation, and this effective integration plays an important role in increasing grain yield and soil fertility. Nutrient stocks were more prevalent in the NT plot when SB was grown than in the other treatment combinations. This may be due to the accumulation of plant residues and the application of suitable cropping patterns.

RT also improves the retention of soil nitrogen (N), which decreases the off-site effects of nutrient losses and increases plant N availability, gross N mineralization, nitrification, and mobilization (Deng et al., 2016). The yields of WW and SB were not significant in the CT and RT1 plots in the first season, which reached a significant level in the third season. The probable reason for the increased yield was related to the elimination of deep soil plowing. Similarly, reducing tillage operations in the RT2 and NT brought progressed crop productivity and improved soil biological, chemical, and physical properties. It is important to note that the impact of conservation tillage is more apparent in the long term rather than in the short term, as soil health develops over time (Islam et al., 2021; Rustamova et al., 2023).

There are no guidelines for assessing whether the tillage system is compatible with certain agroecosystems. Having demonstrated the favorable effect of tillage on maintaining sustainable soil productivity, the CT system may be more suitable for more productive soils, while less fertile soils may benefit more from the RT system implementation (Tobiašová et al., 2023).

In the majority of cases, the advantages of applied conservation tillage are associated with the judicious use of chemicals, i.e., fertilizers, herbicides, and pesticides (Sportelli et al., 2022). In other studies, weed infestations have been described as a limitation of the system, significantly reducing crop yield. Therefore, effective weed control is necessary for successful crop production when NT is used, especially at the initial stage (Ejegue and Gessesse, 2021). However, the majority of publications elucidated the positive features of conservation agriculture in terms of improving soil health, moisture content, crop yield, and yield characteristics. The improved soil characteristics and the decline in bulk density could be associated with crop residue decomposition, which is consistent with the previous reports by Allanov et al. (2019).

A newly introduced agrotechnology must maintain a balance between soil health and crop production while encouraging a strategic and system-oriented approach that reflects the interconnected economic, social, and environmental dimensions of agri-food systems. Since land and water resources are limited, it is necessary to maximize the productive capacity of degraded soils, manage soil organic matter effectively, and improve water usage. Therefore, special attention should be directed to adopting sustainable soil management techniques that can enhance soil health and crop productivity while supporting sustainable ecological functions and ecosystem services (Shen et al., 2018).

Greater awareness of the synergistic benefits of RT and legume-based crop rotation is needed, and agricultural policy schemes should take this into account as a cost-effective strategy for maintaining food supply. Expanding conservation tillage on a large scale is crucial, highlighting the advantages of NT over CT in terms of soil moisture retention, reduced nutrient loss, lower environmental pollution, and decreased resource use, including fuel and labor costs. Adoption of this novelty will rejuvenate agriculture, research, and infrastructure development in the agricultural region with harsh environments. Therefore, long-term studies that may produce more consistent results and the discovery of cultivars suited to conservation tillage should be the main priorities of future studies, considering site-specific functions of this practice in different agroecosystems.

5 Conclusion

The results of this study in arid irrigated land showed that the conservation tillage systems (RT1, RT2, and NT) significantly improved the productivity of WW and SB, as well as soil quality indicators when averaged over the three experimental cycles. Analysis of variance showed that the effect of tillage × vegetation cycle on WW grain yield was significant for NT, RT1, and RT, except for CT in the third vegetation cycle. This outcome shows that a significant impact was achieved by the long-term implementation of conservation tillage practices. The effect of NT was more pronounced when integrated with the WW-SB crop rotation, enhancing WW and SB average grain yield by 27.2 and 30.8%, respectively, compared to CT.

Shifting from conventional to conservation tillage appears to be one of the factors responsible for retaining crop residues, conserving soil moisture, and improving soil health. These land management interventions were further exacerbated by the positive impact of the cereal–legume cropping system, which increased soil nutrient turnover and crop yields subsequently.

This study concludes that the NT technology, combined with the cereal–legume cropping system and residue management, could be considered the best alternative to CT in arid environments. The proven positive impacts of these efficient resource use technologies highlight the urgency of making the transition in arid agriculture to maintain agro-environmental sustainability and food security, considering upcoming climatic constraints.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AN: Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition, Project administration, Supervision. SU: Conceptualization, Writing – original draft, Writing – review & editing, Data curation, Investigation, Methodology, Software. SA: Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. MU: Investigation, Software, Methodology, Writing – original draft, Writing – review & editing. BK: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Methodology. LK: Conceptualization, Resources, Validation, Writing – original draft, Writing – review & editing. FN: Conceptualization, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. ST: Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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