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Effect of tillage, residue and nitrogen management on yield, water and nitrogen use efficiency of wheat (*Triticum aestivum*)

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ABSTRACT

A two-year field study was carried out during winter (*rabi*) seasons of 2020–21 and 2021–22 at the research farm of ICAR-Indian Agricultural Research Institute, New Delhi with the aim of examining the impacts of various methods of tillage, residue management and nitrogen (N) application on wheat (*Triticum aestivum* L.) yield, water use efficiency (WUE), and nitrogen use efficiency in terms of Partial Factor Productivity of Nitrogen (PFPN). The study utilized a split-split plot design with 3 replications, where the main plot consisted of two tillage systems [conventional tillage (CT) and no tillage (NT)], the subplot comprised 2 residue levels [maize residue @5 t/ ha (R+) and no residue (R_0)], and the sub-sub plot involved 3 N levels [60, 120, and 180 kg N/ha, representing 50% (N60 kg N/ha), 100% (N120 kg N/ha), and 150% (N180 kg N/ha)] respectively. The results indicated that both tillage and residue management considerably influenced the grain and biomass yield of wheat. Over the two years, NT exhibited a 7% higher WUE compared to CT, but the change was insignificant. However, in years with lower rainfall, crop residue mulching had a significant positive impact on WUE, while in years with higher rainfall; its effect on WUE was insignificant. Moreover, tillage practices had a considerable effect on the PFPN. In the year 2020–21, PFPN under NT was 3.59% higher than under CT, and in the year 2021–22, it was 2.06% higher. Furthermore, with an increase in N levels, WUE showed a substantial increase, while PFPN decreased.

Keywords: Conventional tillage, Evapotranspiration, Nitrogen use efficiency, No tillage, Water use efficiency, Yield

Agriculture struggles with nutrient and water scarcity, necessitating strategic management for sustained productivity while preserving soil health and the environment. Nitrogen-water interaction is pivotal for crop enhancement, especially in India, where wheat (*Triticum aestivum* L.) cultivation, marked by intensive methods, competes for declining water resources. Traditional tillage poses challenges like carbon depletion, soil erosion and reduced input use efficiency. Sustainable practices like conservation tillage, involving crop residue retention and reduced tillage, offer a promising path forward (Zhang *et al*. 2018). Complex factors determine cereal productivity, emphasizing the need for sustainable practices. Research by Mitra *et al*. (2014) highlights the potential of conservation tillage, with no-till wheat cultivation showing a 14.29% higher yield than conventional methods. Water conservation becomes paramount amid scarcity, achieved through mulching to lower evaporation and enhances soil moisture, ultimately boosting agricultural output. Over a 4-year study, ZT and partial bed planting significantly improved biomass water-use efficiency (49.8 to 66.2%) and reduced water consumption (8.5 to 16.1%) compared to CT plots (Parihar *et al*. 2017). Conservation agriculture further enhances nutrient availability, water retention, and reduces nutrient leaching Verhulst *et al*. (2010). Residue retention improved water productivity in both maize (11.2 to 21.5%) and wheat (12.3 to 19.7% (Naresh *et al*. 2012). In sandy loam soil, residue retention increased moisture storage by 7.7% (Rani *et al*. 2019). Achieving a higher NUE is crucial for enhancing agricultural productivity while also promoting environmental conservation. However, the cultivation of high-yielding and efficient wheat crops cannot be achieved by using disproportionate (Bappa *et al*. 2014) or inadequate amounts of N fertilizers (Yue *et al*. 2012). Efficient tillage practices are crucial for optimizing soil nitrogen recovery and nitrogen use efficiency (NUE) in wheat cultivation. Balancing N fertilizer application is essential for sustainable and productive practices, preventing excessive or inadequate usage. Variability in grain yields among tillage methods and N-rates underscores the complexity of the relationship. This study aims to investigate how tillage, crop residue

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management, and nitrogen application influence wheat yield, water use efficiency (WUE), and NUE in an Inceptisol.

MATERIALS AND METHODS

The field study was carried out during winter (*rabi*) seasons of 2020–21 and 2021–22 at the research farm of ICAR-Indian Agricultural Research Institute, New Delhi. The soil type at the location was sandy loam (Typic Haplustept), originating from the Ganges alluvial deposits. The soil at the experimental site has an average bulk density of 1.57 Mg/m^3, sandy loam texture (0–15 cm), *p*H of 7.8, and organic carbon content of 4.3 g/kg. Additionally, the soil had available nitrogen (N), available phosphorus (P) (measured by the Olsen method), and available potassium (K) contents of 252 kg/ha, 7.3 kg/ha, and 284 kg/ha, respectively. The assessment of various treatments was carried out using a split-split plot design having 3 replications (Table 1). The treatments consisted of two fold primary tillage systems: CT and NT. Additionally, two crop residue mulch (CRM) levels were applied as subplots: maize residue at 5 t/ha (R+) and no residue (R_0). Furthermore, 3 levels of nitrogen were used as sub-subplots: 60, 120, and 180 kg N/ha, representing 50% (N60), 100% (N120), and 150% (N180) of the standard N rate. Wheat (cultivar HD 2967) was planted using a tractor-driven NT seed drill on November 26 and 23 during 2020 and 2021, respectively. The wheat crop was planted with row to row gaps of 22.5 cm and a seeding rate of 100 kg/ha. Harvesting of the crop took place on April 13, 2021, and April 11, 2022, respectively. Under the R + treatment, maize straw mulch was manually laid at a rate of 5 t/ha during the CRI (Crown Root Initiation) stage. Nitrogen was applied in 3 phases: 50% at sowing, 25% during the CRI stage, and the remaining 25% at the flowering stage, using urea as the nitrogen source. During the various growth stages, 5 irrigations were provided to all plots at crucial intervals. Weed control was ensured by carrying out physical weeding 3–4 times during the course of the crop's growth phases.

Growth and yield: The growth and yields of wheat were assessed following the established methodology defined by Nayak *et al*. (2019). To determine the Leaf Area Index (LAI), measurements were taken using the LAI-2000 Plant Canopy Analyzer (LI-COR, USA) at weekly interims. During the crop harvest, grain yield (GY) measurements were carried out in the field. To ensure representative sampling, a 2 × 2 m^2 area was selected from every single plot, carefully avoiding boundary effects. Subsequently, appropriate conversions were applied to express the yields in kg/ha.

Table 1 Treatment details

Main plot (A): Tillage (2)	Sub plot (B): Residue (2)	Sub-sub plot (C): Nitrogen doses (3)
Conventional Tillage (CT)	R+, Apply maize residue @5 t/ha	N50%, 60 kg N/ha (50%RDN)
		N100%, 120 kg N/ha (100% RDN)
No Tillage (NT)	R_0, Without residue	N150%, 180 kg N/ha (150% RDN)

Assessment of evapotranspiration and water use efficiency: The evapotranspiration (ET) of the wheat crop was determined using the water balance technique, which can be expressed by the following equations:

$$ET = P + I + Cp - D - R - \Delta S \quad (1)$$

$$ET = P + I + Cp - D - (Sf - Si) \quad (2)$$

Here, P represents the quantity of precipitation, I indicates the irrigation depth, Cp accounts for capillary rise from the underground water table (which is neglected in this calculation due to the significant depth of the groundwater), D stands for deep percolation loss (assumed to be negligible as moisture content in soil up to 120 cm soil depth was considered), R represents runoff losses (which were absent in this study because bunds were provided for all plots), ΔS represents the variation in storage of soil moisture in the profile, and Si and Sf represent the preliminary and final moisture storage at sowing and harvest, respectively, within the soil profile (0–90 cm).

As a result of neglecting Cp and assuming negligible D and R, the simplified equation becomes:

$$ET = P + I - (Sf - Si) \quad (3)$$

To calculate Water Use Efficiency (WUE), the equation used is as:

$$WUE = GY/ET \quad (4)$$

Where, WUE in kg/m^3 GY in kg/ha and ET in m^3/ha.

Nitrogen use efficiency: NUE in wheat was assessed in terms of Partial Factor Productivity (PFPN) of Nitrogen which was calculated as:

$$PFPN = GY\ (kg/ha)/\ N\ applied\ (kg/ha) \quad (5)$$

Statistical analysis: R software (4.3.1) was used to conduct an analysis of variance (ANOVA) for the split-split plot design (Gomez and Gomez 1984). Least Significant Difference at 5% Probability Level was used to determine the significance of treatment effects and to examine the difference between the means.

RESULTS AND DISCUSSION

Growth and yield: The seasonal variation of wheat's leaf area index (LAI) was examined in relation to different tillage, CRM, and N application practices for the years 2020–21 and 2021–22, as presented in Fig 1(a) and 1(b) separately. The LAI exhibited a polynomial relationship with the number of days after sowing. Interestingly, both tillage and crop residue mulch did not show any noticeable effect on the LAI of wheat for both year. These findings align with earlier research described by Pradhan *et al*. (2018). However, it is worth noting that Yin *et al*. (2016) and Yang *et al*. (2020) reported that LAI was significantly greater under NT as compared to CT. Conversely, an increase in nitrogen doses led to a notable increase in LAI. The maximum LAI values for wheat ranged from 3.72 (CT R_0 N50%) at 115

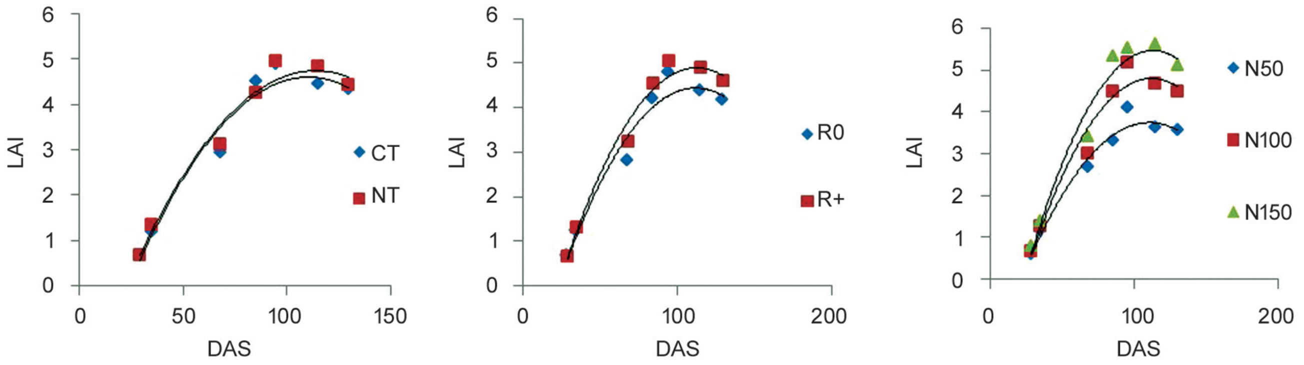

Fig 1(a) Effect of tillage, CRM and N management on LAI of wheat for the year 2020–21.

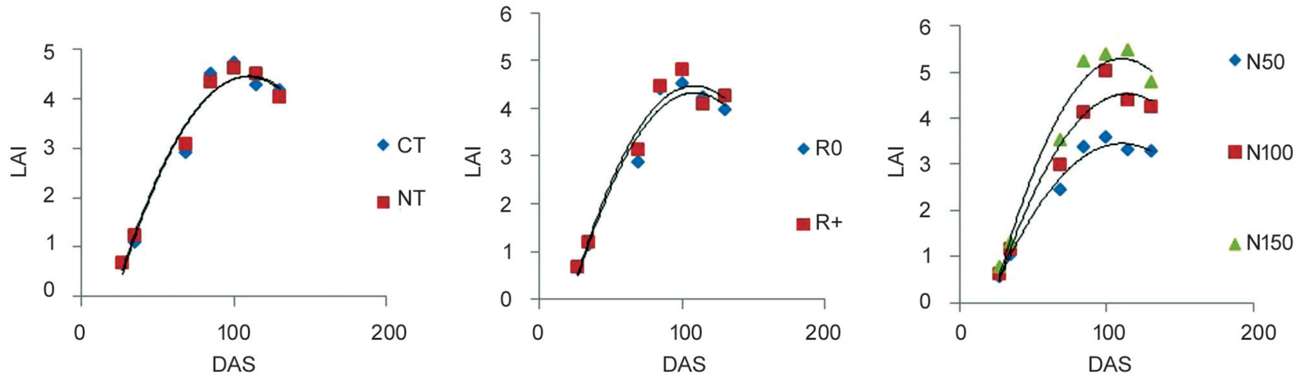

Fig 1(b) Effect of tillage, CRM and N management on LAI of wheat for the year 2021–22.

days after sowing (DAS) to 5.94 (NTR+N150%) at 85 DAS, with an average value of 4.97 for the year 2020–21. For the year 2021–22, the maximum LAI values ranged from 3.6 (CT R_0 N50%) at 115 DAS to 5.97 (NTR+N150%) at 85 DAS, with a mean value of 5.04. On an average, when considering crop residue and N-management, the LAI was higher under NT compared to CT in the year 2020–21 by 0.81% and in the year 2021–22 by 3.14%. Similarly, when looking at tillage and N-management collectively, the maximum LAI under crop residue mulch (CRM) was 6.25% higher in the year 2020–21 and 7.41% in the year 2021–22 compared to treatments without mulch. Crop residue mulch positively influenced LAI by moderating soil temperature, retaining moisture, and conserving water. This led to heightened water uptake, increased photosynthesis, and higher LAI. With 180 kg N/ha, LAI was notably higher than with 120 kg N/ha and 60 kg N/ha, showing increments of 9.82 and 52.60% in 2020–21, and 10.13 and 39.31% in 2021–22. Optimal nitrogen application fosters robust leaf growth and boosts LAI, while reduced nitrogen leads to diminished LAI, aligning with findings from Pradhan *et al.* (2014). This decline in LAI with lower nitrogen doses is attributed to hindered leaf development and reduced photosynthetic activity.

The yield of wheat grain in 2020–21 and 2021–22, under the influence of various tillage, residue, and N-management practices is depicted in Table 2. There was a 1.23% increase in grain yield and a 1.41% increase in biomass yields of wheat from the year 2020–21 to 2021–22. This improvement can be attributed to the greater rainfall received in 2021–22 and the elevated temperatures throughout the crop growth phase. Significantly higher grain yields were observed in plots with NT compared to CT in the year 2020–21. The grain yield varied from 3447 kg/ha (CT R_0 N50%) to 5291 kg/ha (NT R + N150%), with a mean of 4438 kg/ha for 2020–21. In the year 2021–22, the grain yield ranged from 3624 kg/ha (CT R_0 N50%) to 5137 kg/ha (NT R+ N150%). The grain yield was significantly influenced by the type of tillage, residue, and nitrogen level applied ($P<0.0001$). The application of Recommended Dose of Nitrogen (RDN) at 100% and 150% significantly augmented the grain yield by 14.10 and 21.10%, respectively, in the year 2021–22 compared to RDN at 50%. For the year 2020–21, the corresponding increase in grain yield was 29.14 and 36.13%, respectively. These findings are consistent with previous studies by Ghosh *et al.* (2015) and Zhang *et al.* (2018), where they also reported significantly higher grain yield under NT compared to CT. Study conducted by Yuan *et al.* (2023) also reported that no tillage with wheat stubble return improved wheat yield under NT as compared to conventional tillage practices. The impact of various tillage, residue, and nitrogen management practices on the aboveground biomass yield of wheat in the years 2020–21 and 2021–22 is summarized in Table 2. The aboveground biomass varied from 10,413 kg/ha (CT R_0 N50%) to 15,069 kg/ha (NT R+N150%), with an average biomass yield of 13,259 kg/ha in the year 2020–21. In the year 2021–22, the aboveground biomass ranged from 10,848 kg/ha (CT R_0 N50%) to 15,258 kg/ha

(NT R+N150%), with an average biomass yield of 13,071 kg/ha. Notably, under no-tillage (NT), the biomass showed a significant increase of 3.55% compared to conventional tillage (CT). Additionally, the presence of CRM resulted in a 7.01% increase in biomass compared to treatments without residue for the year 2020–21. Likewise, in the year 2021–22, NT showed a 5.63% increase compared to CT, and the effect of CRM on biomass yield exhibited an 11.81% increase compared to plots without residue. Furthermore, biomass yield significantly increased with higher nitrogen levels in both years. On average, in both years, applications of RDN at 100 and 150% resulted in a significantly higher biomass yield than RDN at 50%, with increases of 26.11 and 29.84%, respectively. The interaction between tillage and nitrogen was observed to have a substantial impact on the biomass yield of wheat. However, the tillage × nitrogen × residue interactions were insignificant. In the course of low rainfall year (2020–21), both grain and biomass yields were considerably higher under NT compared to CT, while in the year with higher rainfall, the grain and biomass yields were statistically similar.

Table 2 Grain and biomass yield of wheat, 2020–21 and 2021–22

Treatment	Grain yield (kg/ha)		Biomass yield (kg/ha)	
	2020–21	2021–22	2020–21	2021–22
	Effect of tillage			
CT	4331^{B}	4411^{a}	12696^{B}	13027^{A}
NT	4543^{A}	4572^{a}	13445^{A}	13490^{A}
	Effect of residue			
R_0	4104^{B}	4349^{B}	12627^{B}	12516^{B}
R+	4770^{A}	4634^{A}	13514^{A}	14001^{A}
	Effect of nitrogen			
$N_{50\%}$	3638^{C}	4018^{B}	11366^{C}	11409^{C}
$N_{100\%}$	4698^{B}	4584^{A}	13496^{B}	13899^{B}
$N_{150\%}$	4975^{A}	4873^{A}	14349^{A}	14468^{A}
	Effect of tillage × residue × nitrogen			
CT R_0 $N_{50\%}$	3447^{f}	3624^{d}	10413^{f}	10848^{e}
CT R_0 $N_{100\%}$	4122^{bcd}	4189^{cd}	12800^{cd}	12772^{bc}
CT R_0 $N_{150\%}$	4213^{bc}	4579^{abc}	13075^{c}	12929^{bc}
CT R+$N_{50\%}$	3775^{def}	4515^{abc}	11762^{e}	11739^{de}
CT R+$N_{100\%}$	5140^{a}	4617^{abc}	13470^{bc}	14663^{a}
CT R+$N_{150\%}$	5291^{a}	4942^{ab}	14660^{a}	15211^{a}
NT R_0 $N_{50\%}$	3479^{f}	4220^{bcd}	11329^{ef}	10962^{e}
NT R_0 $N_{100\%}$	4260^{b}	4651^{abc}	13551^{bc}	13111^{b}
NT R_0 $N_{150\%}$	5105^{a}	4834^{abc}	14594^{a}	14472^{a}
NT R+$N_{50\%}$	3852^{cde}	3712^{d}	11963^{de}	12089^{cd}
NT R+$N_{100\%}$	5273^{a}	4880^{abc}	14162^{ab}	15048^{a}
NT R+$N_{150\%}$	5291^{a}	5137^{a}	15069^{a}	15258^{a}
LSD (T)	122	NS	NS	205
LSD (R)	222	278	472	266
LSD (N)	191	368	486	448
LSD (TXRXN)	383	736	973	897

Soil water balance component and ET: Fig 2 illustrates the soil water balance components and seasonal evapotranspiration (ET) for the years 2020–21 and 2021–22, under the impact of various tillage, residue, and N-management practices. Notably, the seasonal ET was lower during 2020–21 compared to the year 2021–22, primarily due to the higher rainfall received in 2021–22. In 2020–21, the overall rainfall during the crop growth phase was 73.6 mm, out of which 66.7 mm was effective rainfall, whereas in 2021–22, the total rainfall was 181.5 mm, with an effective rainfall of 147.8 mm. The seasonal ET values ranged from 386.7 mm (CT R + N100%) to 475.7 mm (CT R_0 N50%) with an average of 432 mm for the year 2020–21. In 2021–22, the values ranged from 387.3 mm (NT R_0 N150%) to 508 mm (CT R_0 N50%) with an average of 438.5 mm. Out of these values, on average, 15% was attributed to changes in effective soil moisture storage (SME), 69.41% to irrigation, and 15.52% to rainfall in the first year. During the second year, the corresponding values were 11.64, 54.71 and 33.70%, respectively. On average, the seasonal ET under NT was 3.16% lower as compared to CT for both years, considering the residue and nitrogen treatments. However, Wang *et al.* (2012) did not notice any substantial variation in seasonal ET caused by CT or NT. When examining both years together, considering tillage and N-management practices together, the cumulative CRM showed an average of 3.38% lower ET compared to treatments without mulch. This observation aligns with the findings reported by Bag *et al.* in (2019). Notably,

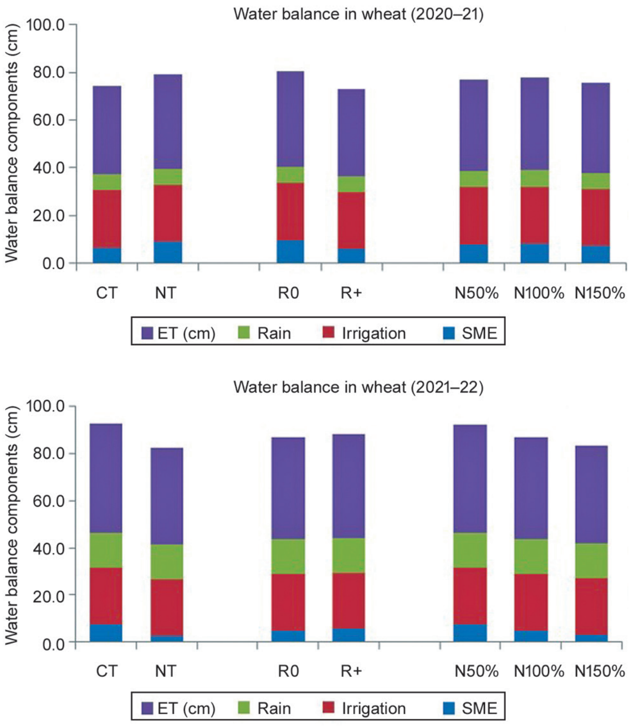

Fig 2 Water balance components of wheat as affected by tillage, CRM and N-management for the year 2020–21 and 2021–22.

Table 3 Water use efficiency and partial factor productivity of nitrogen for wheat, 2020–21 and 2021–22

Treatment	Water use efficiency (kg/ha-mm)		Nitrogen use efficiency (kg grain/kg N)	
	2020-2021	2021-2022	2020-2021	2021-2022
Effect of tillage				
CT	10.4^{A}	9.5^{a}	41.7^{B}	43.6^{A}
NT	10.2^{A}	11.1^{a}	43.2^{A}	44.5^{A}
Effect of residue				
R_0	9.1^{B}	10.1^{A}	39.5^{B}	42.8^{A}
R+	11.5^{A}	10.2^{A}	45.4^{A}	45.3^{A}
Effect of nitrogen				
$N_{50\%}$	8.3^{c}	8.7^{c}	60.6^{a}	66.9^{A}
$N_{100\%}$	11.0^{b}	10.5^{b}	39.1^{b}	38.2^{B}
$N_{150\%}$	11.6^{a}	11.8^{a}	27.6^{c}	27.0^{C}
Effect of tillage × residue × nitrogen				
CT R_0 $N_{50\%}$	7.2^{e}	7.1^{e}	57.5^{b}	60.4^{b}
CT R_0 $N_{100\%}$	9.4^{d}	9.1^{d}	34.3^{d}	34.9^{cde}
CT R_0 $N_{150\%}$	9.8^{d}	11.6^{ab}	23.4^{f}	25.4^{e}
CT R + $N_{50\%}$	9.4^{d}	9.7^{cd}	62.9^{a}	75.2^{a}
CT R + $N_{100\%}$	13.2^{a}	9.9^{cd}	42.8^{c}	38.4^{cd}
CT R + $N_{150\%}$	13.1^{a}	9.9^{cd}	29.3^{e}	27.4^{e}
NT R_0 $N_{50\%}$	7.3^{e}	9.1^{d}	58^{b}	70.3^{ab}
NT R_0 $N_{100\%}$	9.6^{d}	11.4^{bc}	35.5^{d}	38.7^{cd}
NT R_0 $N_{150\%}$	11.3^{c}	12.5^{ab}	29.4^{e}	26.8^{e}
NT R + $N_{50\%}$	9.2^{d}	8.8^{d}	64.2^{a}	61.8^{b}
NT R + $N_{100\%}$	11.9^{bc}	11.8^{ab}	43.9^{c}	40.6^{c}
NT R + $N_{150\%}$	12.2^{b}	13.1^{a}	29.4^{e}	28.5^{de}
LSD (T)	NS	NS	0.7	NS
LSD (R)	0.5	NS	2.3	NS
LSD (N)	0.4	0.8	1.5	5.2
LSD (TXRXN)	0.8	1.6	3.1	10.5

there were no significant differences in seasonal ET due to different nitrogen levels.

Water use efficiency: In 2020–21, wheat's WUE ranged from 7.2 kg/ha-mm (CT R_0 N50%) to 13.2 kg/ha-mm (CT R + N100%), averaging 10.4 kg/ha-mm. In 2021–22, it ranged from 7.1 kg/ha-mm (CT R_0 N50%) to 13.1 kg/ha-mm (NT R+N150%) averaging 10.3 kg/ha-mm (Table 3). Across both years, WUE was about 7.10% higher in NT, although statistically insignificant. Notably, WUE significantly increased by 19.81% with crop residue mulching compared to residue removal. WUE was influenced by tillage and residue interaction and nitrogen levels, showing substantial growth as nitrogen levels rose. Interaction between tillage, nitrogen, and residue significantly impacted WUE, reinforcing the nexus between water, nitrogen, and WUE as supported by Pradhan *et al.* (2014). However, Alvarez and Steinbach (2009) found significantly higher WUE in NT. Higher WUE in NT with residues were also reported in other studies by Ram *et al*. (2013) and Jaswal and Sandal (2023).

Partial factor productivity: PFPN data for wheat in 2020–21 and 2021–22 is displayed in Table 3 considering different tillage, CRM, and N management methods. In 2020–21, tillage significantly affected PFPN, with NT showing a 3.59% increase over CT. In 2021–22, no significant differences were observed between tillage methods. PFPN ranged from 23.4 (CT R_0 N150%) to 64.2 kg grain/kg N (NT R + N50%) in 2020–21 and 25.4 (CT R_0 N150%) to 75.3 kg grain/kg N (CT R+N50%) in 2021–22, with higher values during the wetter year. PFPN decreased notably with higher nitrogen doses (RDN50%, RDN100%, RDN150%) due to nitrogen loss and the non-proportional yield increase. This aligns with findings from researchers Bandyopadhyay *et al.* (2009) and Pradhan *et al.* (2014).

The findings from the present study indicate that tillage, residue, and nitrogen levels had a substantial influence on wheat yield. Crop residue mulching, substantially enhanced water use efficiency particularly, in years with limited rainfall. However, in years with ample rainfall, the impact of CRM on WUE was statistically insignificant. The WUE of wheat showed a significant increase with higher nitrogen levels. Considering nitrogen and residue treatments, the seasonal ET under NT was, on average, lower than under CT for both years. Moreover, increased nitrogen dosages led to a considerable reduction in the PFPN for wheat. Conversely, PFPN significantly increased with crop residue mulching compared to no mulch. In light of these findings, it is suggested to employ NT along with CRM and a nitrogen level of 120 kg N/ha to enhance water use efficiency and nitrogen use efficiency for wheat cultivation in the Indo-Gangetic Plain.

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