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Assessing the Effectiveness of Zero Tillage and Legume-based Cropping Systems for Enhancing Soil Nitrogen Concentrations and Stocks under Rainfed Pearl Millet Production Systems

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Nitrogen (N) is a critical factor in determining the potential yield of crops, and agronomic practices play a crucial role in regulating the forms and availability of N in soils to the plant. Therefore, this study employed a split-plot design, where the main plots were allocated to four tillage methods: zero tillage with crop residue retention (ZT+R), zero tillage with crop residue removal (ZT-R), conventional tillage (CT), and undisturbed soils (UD). The sub-plots were designated for four cropping systems: pearl millet-chickpea (PM-C), pearl millet-chickpea-fodder pearl millet (PM-C-FPM), pearl millet-chickpea-mung bean (PM-C-M), and the natural grasses in UD. The study aimed to understand the effects of different management practices on various forms of N in soil, including mineral-N, hot-water extractable organic N (HWEON), and available N (AvlN), as well as mineral N stock, HWEON stock, and total N stock in different soil layers. The study found that ZT+R significantly increased soil mineral N content and stock by 20% compared to CT across 0-30 cm soil depth. The effects of these practices on mineral-N concentrations were most pronounced in the surface soil layer. Furthermore, ZT practices and legume-based cropping systems enhanced N concentration and its availability. The study also revealed that HWEON content and its stocks were more sensitive to soil tillage practices than cropping systems, with ZT+R having 3.79 times higher HWEON concentration than CT at 0-5 cm soil depth. The significant differences for total N among tillage practices were more pronounced under ZT+R compared to CT. The research highlights the need for using conservation tillage practices, such as ZT+R, in combination with legume-based cropping systems to improve N availability and enhance soil fertility.

Key words: Zero-tillage, cropping systems, mineral nitrogen, hot-water extractable N, N stock, soil depth, pearl millet

Pearl millet (*Pennisetum glaucum*) is a widely cultivated cereal crop in arid and semi-arid regions of the world, including India, Africa, and parts of Asia. It is a hardy crop well adapted to low-input and low-rainfall environments (Meena *et al.* 2023). Pearl millet is a significant food source for millions of people in these regions, particularly in Africa, where it is a staple food crop (FAOSTAT 2023). Pearl millet-based cropping systems face various constraints, including poor soil fertility and a high demand for nutrients, such as nitrogen (N) (Rostamza *et al.* 2011). As a result, N availability in the soil is often limited in pearl millet growing areas, leading to low crop yields and reduced productivity (Meena *et al.* 2023). Therefore, understanding the dynamics of soil N and its uptake by pearl millet is essential for optimizing nutrient management practices and increasing crop productivity.

Conservation agriculture (CA) is a sustainable agricultural management system that has gained popularity in recent years due to its potential to improve soil health, increase crop productivity, and reduce environmental degradation (Page *et al.* 2020). The key principles of CA are the use of minimum tillage, which involves reducing the frequency and intensity of soil disturbance, leaving crop residues on the soil surface, and promoting crop diversity (Sinha

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et al. 2019). Several studies have evaluated the impact of CA on soil N dynamics in different cropping systems. The results indicated that no-till (NT) enhanced total N and total organic N as compared to conventional tillage (CT). Crop residue retention increased nutrients, including available phosphorus (P), cation exchange capacity (CEC), and calcium (Meena *et al.* 2018). Overall, the study suggested that NT with 30% crop residue retention (R) was a better practice to enhance soil fertility in the short-term.

However, the impact of CA on soil N dynamics in pearl millet-based cropping systems is not properly documented, and more research is needed to evaluate the effectiveness of CA in improving soil fertility and crop productivity under these systems. To address this knowledge gap, this research aims to investigate the dynamics of soil N under long-term CA in pearl millet-based cropping systems. The research hypothesis posits that the long-term adoption of CA practices will have varied impacts on soil N fractions and their corresponding stocks, ultimately affecting the N content in both the grain and straw of pearl millet. Understanding soil N dynamics in pearl millet-based cropping systems under CA can help farmers to optimize nutrient management practices, reduce input costs, and increase crop yields, while promoting sustainable agricultural practices that benefit both the environment and human well-being. The results of this study can contribute to the development of effective nutrient management strategies for pearl millet-based cropping systems and promote the adoption of CA practices in rainfed areas.

Materials and Methods

The current research was carried out at the research farm of the ICAR-Indian Agricultural Research Institute (IARI) situated in New Delhi, India. The experimental site is located at a geographical position of 28°38′ N, 77°11′ E with an elevation of 228.6 m above mean sea level. The region experiences a sub-tropical semi-arid climate, characterized by hot and dry summers and cold winters, with an average annual precipitation of 652 mm and average annual temperature of 32 °C. The soil at the experimental site is classified as a Typic Haplustept, originating from Gangetic alluvium. It has a sandy loam texture, consisting of 64.1% sand, 16.9% silt, and 19% clay, and is well-drained, non-saline (EC = 0.32 dS m^{-1}) and alkaline (pH = 7.2) for the 0-15 cm soil depth. The initial soil characteristics include moderate organic carbon (OC) content (4.31 g kg^{-1}), low levels of alkaline permanganate-oxidizable N (145 kg ha^{-1}), medium levels of available P (21 kg ha^{-1}), and available K (174 kg ha^{-1}) for 0-15 cm soil depth. Additionally, the soil has a bulk density of 1.50 Mg m^{-3} at a 0-15 cm soil depth.

Experimental design and standard agronomic practices

The experimental design for this study followed a split-plot approach, with main plots being assigned to four tillage practices: zero tillage with crop residue retention (ZT+R), zero tillage with crop residue removal (ZT-R), conventional tillage (CT) and undisturbed soils (UD). The sub-plots were assigned to four cropping systems: pearl millet-chickpea (PM-C), pearl millet-chickpea-fodder pearl millet (PM-C-FPM), pearl millet-chickpea-mung bean (PM-C-M) and natural grasses present in UD. The CT plots were prepared by deep ploughing followed by two passes of a disc harrow and spring-type cultivator. In contrast, the ZT plots were prepared using a glyphosate spray to eliminate weeds, and a zero-till planter was used for planting. Pearl millet was sown in the rainy season on 15th July 2021 and harvested at the end of the rainy season on 30th September 2021. Chickpea was sown in the winter season on 15th October 2021 and harvested at the end of the winter season on 30th March 2022. Mungbean and fodder pearl millet were sown as summer crops on 1st April 2022. After 25 days, a lifesaving irrigation was given to both crops, and the fodder pearl millet was harvested after 2 months while the mungbean was harvested upon completion of three months. The crops under ZT+R and ZT-R were sown using a happy seeder, which opened the soil in a narrow slit with knife-type tines at a row spacing of 40 cm and left the intra-row areas undisturbed for the second and third crop. The seed-drill machine was calibrated to adjust the seed rate for each crop. Pendimethalin was applied as pre-emergence at 0.75 kg ha^{-1} in 500 litres of water on the next day of sowing. Glyphosate was applied at 1.5 kg ha^{-1} in all plots and peripheral bunds about a week before sowing to kill existing grassy and broad-leaved weeds.

Soil sampling

Soil sampling was conducted in the month of October, following the harvesting of the pearl millet crop, from three different depths, namely 0-5, 5-15, and 15-30 cm. A tube auger was used to collect six random samples from each plot, which were then combined to create a composite sample. These composite samples were placed in labelled plastic bags and stored at a temperature of 4 °C until they were analyzed in the laboratory. The experiment commenced in 2012, and after completing eight cropping cycles, the winter season of 2021-2022 was selected for soil sampling, following the harvesting of the rainy season pearl millet.

Soil and plant analysis

Soil mineral N (NH_4^+-N and NO_3^--N) was extracted using 2*M* KCl at a 1:10 soil to extractant ratio with shaking for 2 hours. The resulting solution was filtered through Whatman 42 filter paper, and the concentration of NH_4^+-N and NO_3^--N in the extract was determined using Kjeldahl apparatus (Rayment and Lyons 2011). Hot-water extractable N was measured following the procedure described by Ghani *et al.* (2003). Soil samples (10 g) were incubated in 50 mL of water in a capped Falcon tube at 80 °C for 16 h. After incubation, the tubes were shaken for 5 min and filtered through a 0.45 μm nylon filter membrane. The hot water extractable organic N (HWEON) was determined using a modified version of the Kjeldahl method, where a solution containing sulphuric acid, and salicylic sulphuric acid was added to a sample. The sample was digested with a Devedras alloy and MgO catalyst at 380 °C for 60 min, after which ammonium was formed and transferred to 2% boric acid. The solution was then titrated with 0.01 *M* HCl to determine HWEON (Bankó *et al.* 2021). Available N by alkaline permanganate method (Subbiah and Asija 1956). Total N in both soil and plant samples (grains and straw) was analyzed using an Isoprime isotope ratio mass spectrometer coupled with a Eurovector elemental analyzer (Isoprime-EuroEA 3000).

The N stock for a layer of soil was calculated using eq. (1)

$$\text{N stock (Mg ha}^{-1}) = \frac{\%\text{N} \times \text{BD (Mg m}^{-3}) \times \text{d(m)} \times 10^4\ \text{m}^2\,\text{ha}^{-1}}{100}$$

where d is soil layer thickness

$$\text{N stock (kg ha}^{-1}) = \text{N stock (Mg ha}^{-1}) \times 1000 \quad (2)$$

Statistical analysis

The statistical analysis of the data obtained from the split-plot design was performed using the "Doebioresearch" package in R software (R Core Team 2022). To determine the significant differences between treatments, the Tukey's HSD test was employed as a post-hoc test, with a significance level of $P<0.05$. The relationship between soil N fractions and N stocks with N in grain and straw were described using the Pearson linear correlation method.

Results and Discussion

Soil mineral-N and its stocks

At 0-5 cm soil depth, NH_4^+-N concentrations were higher in UD and ZT+R treatments, with mean values of 20.8 and 19.8 mg kg^{-1}, respectively, which were significantly ($P \leq 0.05$) greater than those in CT (16.3 mg kg^{-1}) and ZT-R (14.0 mg kg^{-1}) treatments at the same depth. The PM-C-M cropping system exhibited significantly higher soil NH_4^+-N concentrations than other treatments at the 0-5 cm soil depth. There were no significant differences among cropping systems at 5-15 and 15-30 cm soil depths. The interaction between tillage and cropping systems was only significant at 0-5 cm soil depth. Specifically, the trend observed for the interaction between tillage and cropping systems was CT:PM-C-FPM = CT:PM-C-M = ZTR:PM-C-M > ZTR:PM-C = ZT(-R):PM-C-M > CT:PM-C = UD:NG > ZT(-R):PM-C-FPM = ZT(-R):PM-C (Table 1). The results suggest that soil NH_4^+-N concentrations are influenced by both soil tillage and cropping system practices. At the 0-5 cm soil depth, the UD and ZT+R treatments had significantly higher NH_4^+-N concentrations compared to the CT and ZT-R treatments. This result is consistent with previous studies showing that reduced tillage and residue retention practices lead to increased NH_4^+-N concentrations in soil (Dey *et al.* 2017; Tigga *et al.* 2022). The inclusion of legumes in the crop rotation enhanced both soil fertility and crop yield by facilitating N fixation and subsequent release into the soil, particularly in the surface layers (Chaudhary *et al.* 2019a). Reduced tillage with residue retention improved soil organic matter (SOM) storage, which is primary source of NH_4^+-N and it is positively associated with SOM (Diekow *et al.* 2005).

Soil NO_3^--N concentrations were significantly higher in ZT+R (24.9 mg kg^{-1}), CT (23.1 mg kg^{-1}), and UD (23.3 mg kg^{-1}) tillage practices compared to ZT-R at a soil depth of 0-5 cm (Table 1). At lower depths, ZT+R and ZT-R had significantly higher soil NO_3^--N concentration compared to other tillage treatments. This result is consistent with previous studies showing that reduced tillage practices can lead to increased NO_3^--N concentrations in soil (Dey *et al.* 2018; Chaudhary *et al.* 2019b; Tigga *et al.* 2022). At 5-15 and 15-30 cm soil depths, both ZT+R and ZT-R had the highest soil NO_3^--N concentrations compared with other tillage practices (Table 1). The anionic

Table 1. Ammonium (NH_4^+-N) and nitrate (NO_3^--N (mg kg^{-1}) concentration in soil after harvesting of *kharif* pearl millet

Treatments	NH_4^+-N (mg kg^{-1})			NO_3^--N (mg kg^{-1})		
	0-5 cm	5-15 cm	15-30 cm	0-5 cm	5-15 cm	15-30 cm
Tillage practices						
ZT+R	19.8^{ab}	16.6^{a}	11.6^{a}	24.9^{a}	25.7^{a}	14.0^{a}
ZT-R	14.0^{c}	15.6^{a}	11.2^{a}	17.5^{b}	21.8^{ab}	11.5^{ab}
CT	16.3^{bc}	15.2^{a}	8.59^{a}	23.1^{a}	20.9^{b}	9.68^{b}
UD	20.8^{a}	13.0^{a}	10.2^{a}	23.4^{a}	20.1^{b}	8.13^{b}
Cropping systems						
PM-C-M	20.7^{a}	16.7^{a}	11.6^{a}	24.2^{a}	25.3^{a}	12.7^{a}
PM-C-FPM	17.5^{b}	16.0^{a}	10.2^{a}	21.7^{ab}	21.8^{ab}	10.9^{ab}
PM-C	16.3^{c}	14.7^{a}	9.60^{a}	19.6^{b}	21.3^{b}	11.7^{ab}
NG	16.3^{c}	13.0^{a}	10.2^{a}	23.4^{ab}	20.1^{b}	8.13^{b}
Tillage × cropping systems						
ZTR:PM-C-M	21.9^{ab}	18.9^{a}	12.8^{a}	28.1^{a}	30.2^{a}	15.1^{a}
ZTR:PM-C-FPM	17.7^{cd}	14.3^{a}	11.4^{a}	22.3^{abc}	23.2^{ab}	12.5^{abc}
ZTR:PM-C	19.8^{bc}	16.4^{a}	10.7^{a}	24.3^{ab}	23.6^{ab}	14.4^{ab}
ZT(-R):PM-C-M	17.3^{cd}	17.0^{a}	12.4^{a}	18.0^{cd}	24.0^{ab}	13.5^{abc}
ZT(-R):PM-C-FPM	12.1^{e}	16.6^{a}	9.63^{a}	20.2^{bcd}	23.3^{ab}	10.7^{abc}
ZT(-R):PM-C	12.5^{e}	13.0^{a}	11.6^{a}	14.2^{d}	18.2^{b}	10.3^{abc}
CT:PM-C-M	22.9^{a}	14.0^{a}	9.53^{a}	26.4^{a}	21.6^{ab}	$9.40b^{c}$
CT:PM-C-FPM	22.8^{a}	16.9^{a}	7.80^{a}	22.7^{abc}	18.9^{b}	$9.33b^{c}$
CT:PM-C	16.7^{d}	14.6^{a}	8.43^{a}	20.3^{bc}	22.1^{ab}	10.3^{abc}
UD:NG	16.3^{d}	12.9^{a}	10.2^{a}	23.4^{abc}	20.1^{b}	8.13^{c}

nature of soil NO_3^--N imparts a negative charge, rendering it incapable of retention on clay minerals. Consequently, NO_3^--N consistently resides in the soil solution, making it susceptible to leaching. The experimental site exhibits a sandy loam texture characterized by elevated sand content, thereby facilitating the leaching of NO_3^--N from 0-5 to 5-15 cm soil depth (Choudhary *et al.* 2019b). Contrastingly, at 15-30 cm, there is a rapid decline in soil NO_3^--N concentrations. This phenomenon can be attributed to an elevated soil pH at this lower depth, instigating denitrification processes wherein NO_3^--N is subjected to loss. Consequently, diminished values of NO_3^--N are discerned at the 15-30 cm soil depth (Zhang *et al.* 2016; Mitchell *et al.* 2017; Virk *et al.* 2022).

Regarding cropping systems, PM-C-M, PM-C-FPM, and UD had 23.4, 10.9, and 19.3 per cent higher soil NO_3^--N concentrations over PM-C at 0-5 cm soil depth. At 5-15 cm soil depth, PM-C-M (25.3 mg kg^{-1}) and PM-C-FPM (21.8 mg kg^{-1}) had significantly higher soil NO_3^--N concentrations compared to PM-C and NG. At 15-30 cm soil depth, PM-C-M, PM-C-FPM, and PM-C had similar soil NO_3^--N concentrations but were significantly higher than NG. Furthermore, the study found that the interaction between tillage and cropping systems was significant at all three soil depths (Table 1). This result may be due to the inclusion of leguminous crops in these systems, which can contribute to increased N availability in the soil (Virk *et al.* 2022). At the 5-15 cm soil depth, the PM-C-M and PM-C-FPM systems had significantly higher NO_3^--N concentrations compared to PM-C and NG, indicating that these systems may be more effective at managing soil N at this depth. At the 15-30 cm soil depth, all three PM-C systems had similar NO_3^--N concentrations but were significantly higher than NG.

At 0-5 cm soil depth, CT had approximately 39% higher mineral N stock compared to ZT-R, which was statistically significant ($P<0.05$) (Fig. 1). At 5-15 cm soil depth, ZT+R had around 27 per cent higher mineral N stock than UD, while at 15-30 cm soil depth, ZT+R had 35.8 per cent higher mineral N stock compared to UD (Fig. 1). This indicates that CT may lead to increased availability of N in the soil at shallow depths due to higher rate of SOM mineralization due to tillage practices and better mixing of crop residues in soil exposing it to oxidation and mineralization (Page *et al.* 2020). Among cropping systems, PM-C had the lowest mineral N stock (22.74 kg ha^{-1}) at 0-5 cm soil depth, while other treatments had higher and similar mineral N stock. At 5-15 cm soil depth, PM-C-M had 29 per cent higher ($P<0.05$) mineral N stock than natural grasses. At 15-30 cm soil depth, the mineral N stock followed this trend: PM-C-M > PM-C > PM-C-FPM > UD (Fig. 1).

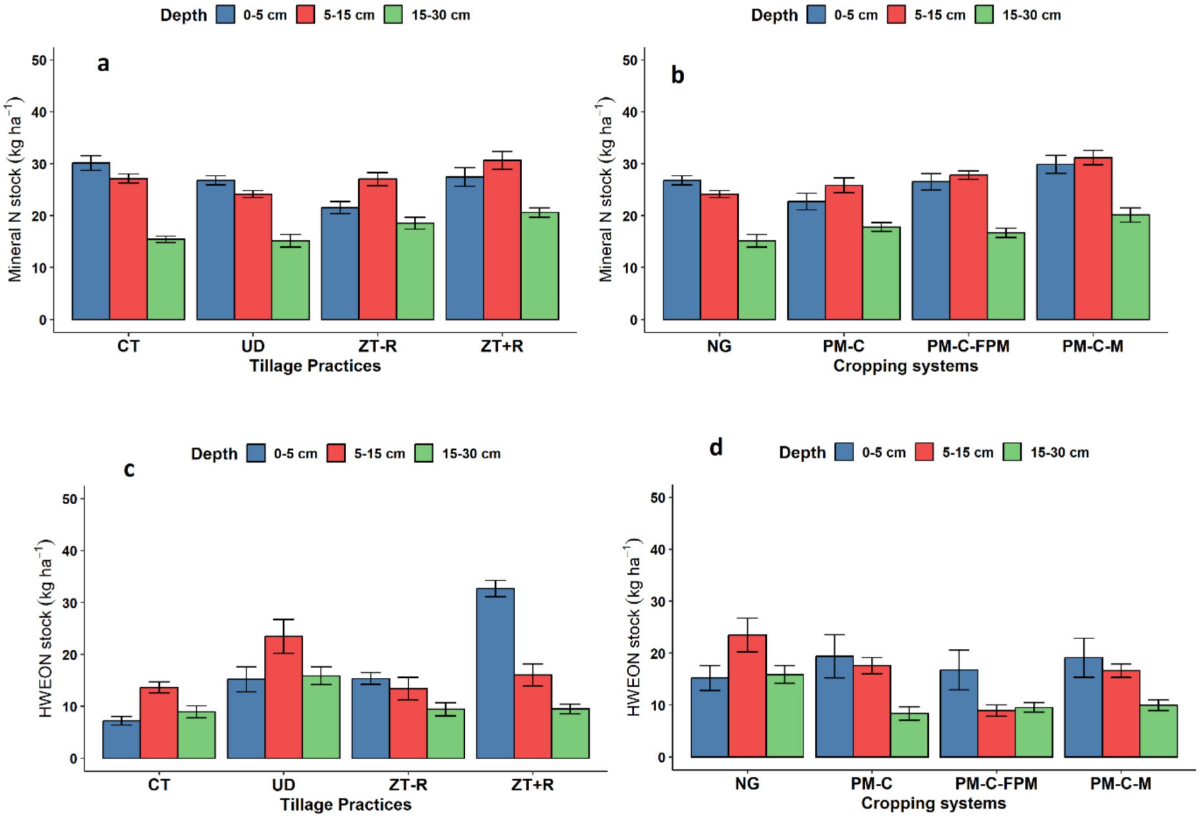

Fig. 1. Stocks of mineral N and HWEON after harvesting of pearl millet in different tillage and cropping system
Error bars represent the standard error of the mean

These findings suggest that tillage practices and cropping systems can significantly impact the distribution of mineral N in the soil (Zhang *et al.* 2016; Mitchell *et al.* 2017; da Silva *et al.* 2020; Tigga *et al.* 2022).

Hot-water extractable N

The concentration of HWEON varied among different tillage and cropping systems and soil depths. The ZT+R had the highest HWEON concentration (50.5 mg kg^{-1}) at 0-5 cm soil depth, while CT had the lowest concentration (10.5 mg kg^{-1}) (Table 2). Compared to CT, ZT+R, ZT-R, and UD had 3.79, 1.12, and 1.14 times higher HWEON concentration at 0-5 cm soil depth, respectively. At 5-15 cm soil depth, HWEON concentration was similar in ZT+R (32.0 mg kg^{-1}) and ZT-R (22.0 mg kg^{-1}), with values significantly higher compared to CT and UD. The UD had significantly higher HWEON concentration (19.0 mg kg^{-1}) than other tillage practices at 15-30 cm soil depth (Table 2). This could be attributed to the increased SOM and N mineralization under reduced tillage practices (ZT+R, ZT-R) and undisturbed soils as reported by several previous studies (Mulvaney *et al.* 2010). At 5-15 cm soil depth, the ZT+R and ZT-R treatments had higher HWEON concentrations compared to CT and UD, which may be due to the accumulation of N in the upper soil layer under the CT practices (Zhang *et al.* 2016).

The highest HWEON concentration (32.0 mg kg^{-1}) was observed in the NG at 5-15 cm soil depth, while other cropping systems had similar HWEON concentrations. At 15-30 cm soil depth, NG had significantly higher HWEON concentration (19.0 mg kg^{-1}) than other treatments. The interaction between tillage and cropping systems for HWEON content was significant at all three soil depths (Table 2). At 15-30 cm soil depth, the NG had significantly higher HWEON concentration compared to other treatments. This could be due to N accumulation in deeper soil layers through leaching or root exudation from natural grasses (da Silva *et al.* 2020; Piazza *et al.* 2020). Furthermore, the interaction between tillage and cropping systems for HWEON content was significant at all three soil depths. This indicates that the effect of tillage practices on HWEON concentration may vary with different crop rotations and *vice versa.*

Table 2. Hot water extractable N and available N concentration in soil under different tillage and cropping practices

Treatment	HWEON (mg kg^{-1})			Available N (mg kg^{-1})		
	0-5 cm	5-15 cm	15-30 cm	0-5 cm	5-15 cm	15-30 cm
Tillage practices						
ZT+R	50.5^{a}	32.0^{a}	11.8^{b}	118^{a}	118^{a}	56.4a
ZT-R	22.3^{b}	22.0^{ab}	11.6^{b}	72.2^{c}	137^{a}	39.6c
CT	10.5^{c}	18.0^{b}	10.5^{b}	101^{b}	127^{a}	45.4b
UD	22.5^{b}	19.0^{b}	19.0^{a}	101^{b}	138^{a}	55.9a
Cropping systems						
PM-C-M	29.1^{a}	22.0^{b}	12.0^{b}	99.6^{ab}	116^{b}	45.9b
PM-C-FPM	25.1^{a}	12.0^{c}	11.6^{b}	80.0^{b}	136^{a}	49.1b
PM-C	29.0^{a}	24.0^{b}	10.4^{b}	112^{a}	131^{a}	46.0b
NG	22.5^{a}	32.0^{a}	19.0^{a}	101^{ab}	138^{a}	55.9a
Tillage × cropping systems						
ZTR:PM-C-M	51.6^{a}	25.0^{ab}	10.0^{ab}	114^{ab}	112^{bc}	40.4^{bcd}
ZTR:PM-C-FPM	46.7^{a}	11.6^{cd}	10.6^{ab}	89.9^{b}	125^{ab}c	54.8^{abc}
ZTR:PM-C	53.1^{a}	30.0^{a}	15.0^{ab}	150^{a}	118^{abc}	40.1^{bcd}
ZT(-R):PM-C-M	23.1^{b}	25.0^{ab}	16.0^{ab}	84.9^{b}	134^{ab}	36.7^{cd}
ZT(-R):PM-C-FPM	20.5^{b}	8.00^{d}	10.0^{ab}	48.2^{c}	133^{abc}	52.5^{abc}
ZT(-R):PM-C	23.3^{b}	22.0^{abc}	9.00^{ab}	83.6^{bc}	145^{a}	29.6^{d}
CT:PM-C-M	12.7^{b}	17.0^{bcd}	10.4^{ab}	99.2^{b}	102^{c}	60.7^{ab}
CT:PM-C-FPM	8.30^{b}	16.0^{bcd}	15.0^{ab}	102^{b}	149^{a}	40.1^{bcd}
CT:PM-C	10.6^{b}	21.0^{abc}	7.00^{b}	102^{b}	130^{abc}	68.0^{a}
UD:NG	22.5^{b}	32.0^{a}	19.0^{a}	101^{b}	138^{ab}	56.0^{abc}

At 0-5 cm soil depth, ZT+R had the highest HWEON stock (32.66 kg ha^{-1}), which was 3.53 times higher than CT, indicating the potential for reduced tillage and residue retention to increase HWEON stock. At 5-15 cm soil depth, UD and ZT+R had 75 and 20 per cent higher HWEON content than ZT-R, respectively, highlighting the importance of soil disturbance in HWEON accumulation. Among all treatments, UD had the highest HWEON stock (15.88 kg ha^{-1}), which was 77.44 per cent higher than CT, demonstrating the influence of tillage practice on HWEON stock (Fig. 1). Interestingly, the results suggest that cropping systems do not significantly affect HWEON stocks at 0-5 cm soil depth. However, at 5-15 cm soil depth, natural grasses had about 1.63 times higher HWEON stock than PM-C-FPM cropping systems, indicating the potential benefits of grasses for increasing soil HWEON stock. Natural grasses also had the highest HWEON stock (15.88 kg ha^{-1}) compared to other treatments at 15-30 cm soil depth, suggesting that deeper soil layers may benefit from grasses in terms of HWEON accumulation. This suggests that natural grasses can improve soil fertility and enhance HWEON accumulation. Additionally, natural grasses had the highest HWEON stock (15.88 kg ha^{-1}) at the 15-30 cm soil depth, highlighting their potential for HWEON accumulation in deeper soil layers (Diekow *et al.* 2005; Sainju *et al.* 2012).

Available N

Highest available N concentration was found in ZT+R (118.2 mg kg^{-1}), while the lowest was found in ZT-R (72.2 mg kg^{-1}) at 0-5 cm soil depth. There was no significant difference among tillage practices at 5-15 cm soil depth. At 15-30 cm soil depth, ZT+R (56.4 mg kg^{-1}) and UD (55.9 mg kg^{-1}) had significantly higher available N concentration than CT (45.4 mg kg^{-1}) and ZT-R (39.6 mg kg^{-1}). These finding is consistent with previous studies that have reported higher available N concentrations in ZT systems that involve residue retention compared to conventional tillage systems (Page *et al.* 2020). The higher available N concentration in ZT+R could be attributed to the increased organic matter content and improved soil structure, which enhance crop nutrient cycling and crop uptake (da Silva *et al.* 2020). The highest available N was observed at 5-15 cm soil depth, followed by 0-5 cm and least under 15-30 cm soil depth (Fig.2). This may be due to loss of available N due to erosion, leaching and denitrification at surface layers which was reduced at 5-15 cm soil depth (Lal and Stewart 2018).

Total N

The total N stock at 0-5 cm soil depth varied significantly among different tillage practices, with ZT+R having the highest total N stock followed by

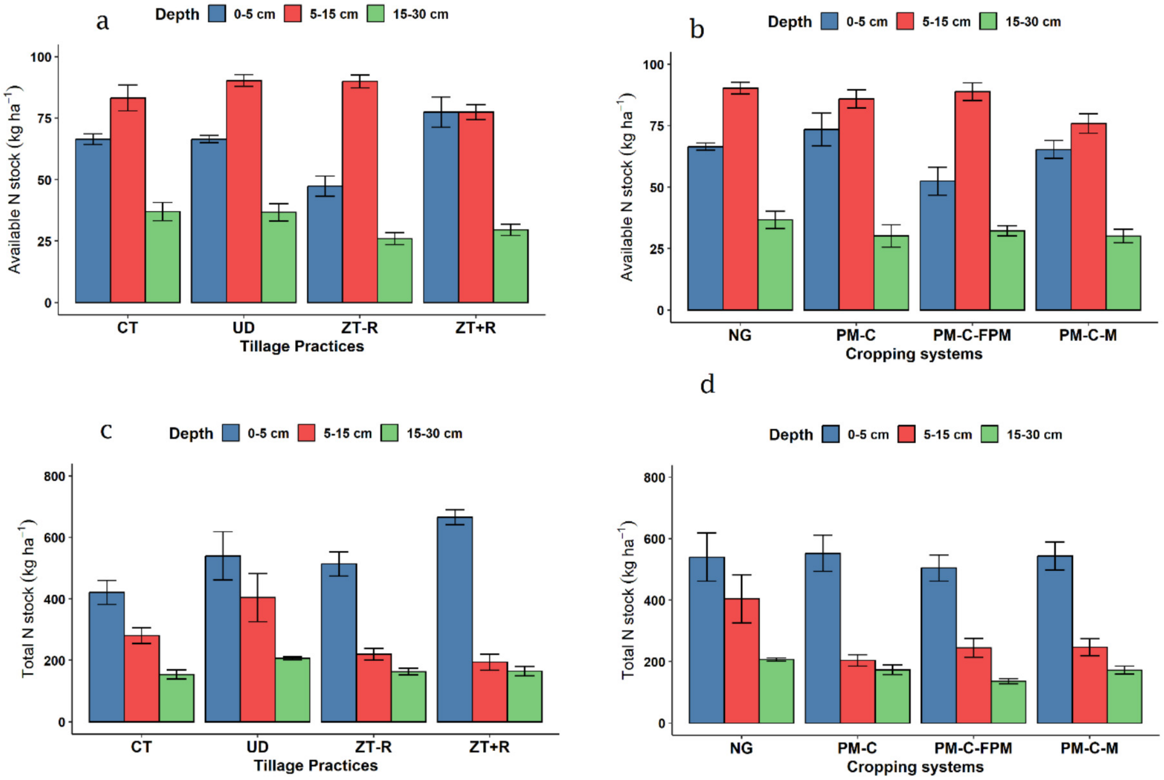

Fig. 2. Stocks of available N and total N after harvesting of pearl millet under different tillage and cropping practices
Error bars represent the standard error of the mean

UD, ZT-R, and CT. Specifically, ZT+R, UD, and ZT-R treatments had 58, 28, and 22 per cent higher total N stocks, respectively, than CT ($P<0.05$). At 5-15 cm soil depth, UD had the highest total N stock (404 kg ha^{-1}), which was 107 per cent higher than that of ZT-R (Fig.2). This suggests that undisturbed soils with natural grasses may have protected total N stock than extractive cropping systems, especially at deeper soil depths. This is consistent with previous studies that have shown the potential for grasses to improve SOM and N stocks due to their deep rooting and high biomass production (Zhang *et al.* 2016; Chen *et al.* 2019). In addition, several researchers have reported that the inclusion of legumes in cropping systems improved soil N stock and SOM content, resulting in higher crop productivity (Sisti *et al.* 2004; Chen *et al.* 2019; Piazza *et al.* 2020).

Nitrogen concentration in pearl millet grain and straw

The tillage practices and cropping systems did not significantly impact the nutrient concentration in both grain and straw, except for N concentration in the grain, which was affected by both tillage practices and cropping systems. N concentration in grain and straw of pearl millet was 1.50 and 0.54%, respectively. No significant differences were observed in nutrient concentration in both grain and straw among different tillage practices and cropping systems (Fig. 3).

Correlation

Nitrogen in grain and straw did not significantly correlated with other soil properties. Whereas, NH_4^+-N is strongly ($p<0.01$) is significantly correlated with other N fractions and N stocks. Similar to NH_4^+-N, NO_3^--N, HWEON and available N were also strongly correlated with other N fractions and stocks (Table 3). The present study found that neither tillage practices nor cropping systems significantly affected the nutrient concentration in both grain and straw, except for N concentration in grain. The highest N concentration in the pearl millet grain was observed under the ZT+R and PM-CP-MB systems. This result suggests that tillage practices and cropping systems may not significantly determine nutrient concentrations in grain and straw, except for N. This finding is in line with previous research that showed no significant differences in nutrient concentrations in grain and straw under different tillage practices and cropping systems (Rostamza *et al.* 2011).

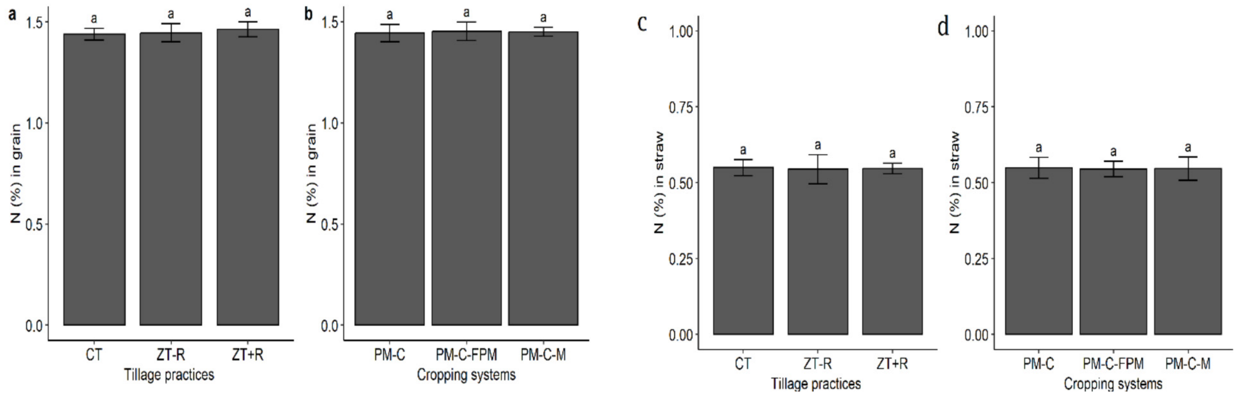

Fig. 3. Concentration of N in grain and straw under different tillage and cropping systems

Table 3. Correlations of N fractions in soil with N content in grains and straw

Parameters	Grain N	Straw N	NH_4^--N	NO_3^--N	HWEON	Avail N	Total N	Mineral N stock	HWEON stock	Avail N stock
Straw N	-0.253									
NH_4^+-N	0.076	-0.035								
NO_3^--N	0.102	0.073	0.405^{**}	0.433^{**}						
Avail N	-0.020	0.016	0.556^{**}	0.650^{**}	0.405^{**}					
Total N	0.182	-0.003	0.574^{**}	0.450^{**}	0.628^{**}	0.331^{**}				
Mineral stock	-0.020	-0.033	0.831^{**}	0.917^{**}	0.273^{**}	0.581^{**}	0.317^{**}			
HWEON stock	0.112	0.064	0.340^{**}	0.381^{**}	0.991^{**}	0.376^{**}	0.553^{**}	0.235^{*}		
Avail N stock	-0.020	0.016	0.556^{**}	0.650^{**}	0.405^{**}	1.000^{**}	0.331^{**}	0.581^{**}	0.376^{**}	
Total N stock	0.235	-0.047	0.072	0.119	0.703^{**}	0.350	0.984^{**}	-0.100	0.688^{**}	0.350

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailled).

Conclusions

The present study has demonstrated that tillage practices and cropping systems have significant effects on soil N stocks in different soil layers. The results suggest that reduced tillage practices, residue retention, and the inclusion of leguminous crops in cropping systems can increase NH_4^+-N, NO_3^--N, HWEON, and available N concentrations, as well as improve total N stocks in the soil. However, the effects of these practices may vary with soil depth and crop rotation. Based on the results of the present study, it can be concluded that ZT+R is a more effective CA practice for maintaining soil N stocks and improving soil health than CT. The study found that ZT+R had comparable N stocks to undisturbed soils, which suggests that this practice can help to conserve soil N and prevent depletion over time. Additionally, ZT+R was found to have higher labile N fractions, such as mineral N and available N, than undisturbed soils, which indicates that this practice can also improve soil fertility and nutrient availability. Overall, the findings of this study suggest that adopting CA practices, such as ZT+R, can be beneficial for maintaining and improving soil health. By conserving soil N and improving soil fertility, these practices can help support healthy crops' growth, reduce nutrient losses, and promote sustainable agriculture.

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