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Distribution of mineral nitrogen in long-term conservation agriculture under semi-arid condition

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ABSTRACT

Depthwise and temporal distribution of soil nitrogen release was carried out in pigeon pea [*Cajunus cajan* (L.) Millsp.] under conservation agriculture (CA) experiment (since 2010) during *kharif* 2019–20. The treatment includes conventional tillage (CT) and zero tillage (ZT), which includes: permanent narrow bed (PNB); PNB with residues of previous crop (PNB+R); permanent broad bed (PBB), PBB with residues (PBB+R), flat bed (FB) and FB with residues (FB+R). Soil samples were collected at different stages; pre-flowering, flowering, pod filling and harvest of pigeon pea from two depths (0-15 and 15-30 cm). Adopting CA practices increased NH_4-N, NO_3-N and mineral N over without CA plots irrespective of crop growth stages and depth of soil. As soil depth increases, NH_4-N, NO_3-N and mineral-N decreased and the reduction was more under CT and ZT without residues retained plots. The maximum NH_4-N was observed at the flowering stage followed by pod filling > pre-flowering > harvest stage in 15 cm soil depth. The average NO_3-N decreased from pre-flowering (34.3 mg/kg) to flowering (28.7 mg/kg) and increased at the pod filling stage (33.7 mg/kg). Among all treatments, PBB+R recorded significantly higher NH_4-N, NO_3-N, and mineral-N. In nutshell, adopting CA practices (PBB+R) may be a viable option for enhancing N availability, especially in semi-arid and arid conditions where N is always a limiting factor for crop growth and yield.

Keywords: Ammonia nitrogen, Conservation agriculture, Inceptisol, Mineral nitrogen, Pigeon pea

Nitrogen (N) a crucial nutrient in both agricultural and natural ecosystems, influencing soil microbial biodiversity, plant-soil interactions and overall ecosystem functioning. However, the concentration of N in soil differ significantly with vegetation and type of residue added in the soil, texture, *p*H, aeration, temperature, organic matter content of the soil, management practices such as tillage and input of nutrients (Debnath *et al.* 2015). Tillage is one of the major practices affecting soil organic matter, which, consequently affects the N transformation process (Kihara *et al.* 2012). Conventional tillage practice is most common among farmers, negatively affects soil fertility and productivity over the long-term due to soil erosion and loss of organic matter. To overcome this, conservation agriculture (CA) adopted in many parts of the world with several advantages. The CA system combines agronomic practices that minimize mechanical soil disturbance, maintains permanent soil cover by using crop residues and cover crops, and includes crop rotation. The positive effects of zero tillage enhanced soil quality by decreasing soil bulk density, enhancing microbial activity, increasing soil organic content etc. (Jina *et al.* 2011). Nitrogen mineralization is largely affected by tillage, diversified crop rotations and manuring, different pools of soil N, as well as total soil N with a concomitant increase in total SOC (Yadav *et al.* 2017). It is also argued that perceiving the overall process is more important in semi-arid regions because these regions are inherently low in nitrogen. Therefore, system-specific N conservation methods, owing to the fundamentally different management practices than conventional tillage, must be developed. We hypothesized that residue retention would reduce the nitrogen losses and, with time, contribute to the available pool via decomposition. Land configurations may affect the distribution of nitrogen in soil at various depths. Therefore the objective of this study was to investigate the effects of conservation agriculture and different crop establishment systems on temporal and spatial distribution of N availability and its distribution in soil over conventionally managed pigeon pea [*Cajunus cajan* (L.) Millsp.]-wheat (*Triticum aestivum* L.) cropping.

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MATERIALS AND METHODS

The experimental site was located at 28°35′N latitude, 77°12′E longitude and 228 m amsl at ICAR-Indian

Agricultural Research Institute, New Delhi. The soil of the experimental field was sandy clay loam in texture with *p*H 7.7 (1:2.5 soil: water), EC 0.64 dS/m. The $KMnO_4$ oxidizable organic carbon 5.2 g/kg, available N 183 kg/ha, 0.5M $NaHCO_3$ extractable P 23.3 kg/ha and 1 N NH_4OAc extractable K 250 kg/ha.

Treatment details: Conservation agricultural practices based pigeon pea-wheat system was continuing since 2010 at the ICAR-Indian Agricultural Research Institute (IARI), New Delhi. During 2010–2011, the field experiment was conducted with five treatments arranged in a randomized block design (RBD) with three replications. The treatments combinations were conventional tillage and flat-bed sowing without residue recycling (CT), zero tilled permanent narrow-bed sowing without residue retention (PNB), zero tilled permanent narrow-bed sowing with residue retention (PNB+R), zero tilled permanent broad-bed sowing without residue retention (PBB), zero tilled permanent broad-bed sowing with residue retention (PBB+R). Two additional treatments were employed in the next year (2011–12): zero tilled flat bed sowing without residue retention (ZT) and zero tilled flat bed sowing with residue retention (ZT+R). The plot size was 9.0 m × 8.4 m. Fresh raised beds were prepared under CT, while permanent beds, reshaped once a year. In the first year of the experiment, an average quantity of 2.6 Mg/ha (fresh weight basis) wheat residue was retained for PNB+R and PBB+R plots. Later on, roughly 20% and 40% of pigeon pea and wheat residues were maintained in all residue retention plots, respectively. Pigeon pea residue comprised the leaves and tender twigs, while the wheat residue was kept as such after harvesting using a combine harvester. In 2019–20, pigeon pea (cv. Pusa Arhar 16) was sown in June and harvested in November. The basal dose of 20 kg N/ha, 80 kg P_2O_5/ha, and 40 kg K_2O/ha was applied 10 days after sowing.

Soil sampling and analysis: The soil sampling was performed at four critical crop growth stages of pigeon pea from two soil depths (0–15 and 15–30 cm) at 60, 75, 110 and 145 days after sowing which resemble to pre-flowering, flowering, pod filling and harvesting stages of crop respectively. Composite soil samples (15 random samples from each plot thoroughly mixed to one) in triplicate were collected using augur tube. In case of PNB plots, 10 samples were collected from beds and 5 samples from furrow areas from each plot, further mixed to make one. Whereas, in PBB plots, 12 samples were collected from beds and 3 samples from furrow areas from each plot, further mixed to make one. Samples were tagged and transported to the laboratory. Thereafter, the soil was air dried, sieved (2 mm mesh size), and homogenized. The initial characteristic of soil, i.e. pH, electrical conductivity, soil texture, Walkley and Black carbon (soil organic carbon), available nitrogen, available phosphorus, available potassium was estimated using standard protocols. The ammonium and nitrate nitrogen were extracted from the soil as per the method suggested by Keeney and Nelson (1982), and estimated through flow injector analysis (FIAstar 5000-FOSS).

Statistical analysis: The statistical analyses of the data were carried out by procedures suggested by Gomez and Gomez (1984) for randomized block design (RBD) of the experiment. Calculation of Analysis of variance (ANOVA) and Tukey Honest significant different test (Tukey HSD) was conducted using SAS v 9.3. The significance referred to in the results is P<0.05.

RESULTS AND DISCUSSION

Ammonium-N (NH_4-N): In general, the adoption of CA practices (after 10 years) increased ammonium nitrogen concentration in soil at different crop growth stages (Table 1). At different physiological crop growth stages, the highest NH_4-N concentration in soil was recorded in PBB+R plots, and it was 131, 100, 77, and 73% higher than CT plots at the

Table 1 Ammonium nitrogen (mg/kg soil) concentration in soil at different growth stage of pigeon pea under conservation agriculture

Treatment	Pre-flowering	Flowering	Pod filling	Harvest	Mean	Pre-flowering	Flowering	Pod filling	Harvest	Mean
	0-15 cm					15-30 cm				
CT	6.8^{D}	17.4^{D}	12.2^{E}	6.6^{B}	10.7^{D}	3.8^{E}	6.1^{D}	4.4^{C}	3.8	4.5^{B}
PNB	7.8^{D}	23.0^{C}	16.3^{CD}	7.9^{B}	13.8^{BCD}	4.5^{DE}	5.0^{D}	5.3^{BC}	3.2	4.5^{B}
PNB+R	10.0^{C}	29.7^{B}	16.8^{C}	8.7^{AB}	16.3^{ABC}	4.6^{DE}	9.2^{BC}	5.8^{B}	2.9	5.6^{AB}
PBB	10.3^{C}	24.1^{C}	15.7^{CD}	7.3^{B}	14.3^{BCD}	6.0^{C}	7.9^{C}	4.8^{BC}	3.6	5.6^{AB}
PBB+R	15.7^{A}	34.8^{A}	21.6^{A}	11.4^{A}	20.9^{A}	10.5^{A}	12.5^{A}	7.4^{A}	3.7	8.5^{A}
FB	8.7^{CD}	18.0^{D}	14.8^{D}	7.7^{B}	12.3^{CD}	5.6^{CD}	8.2^{C}	5.4^{BC}	3.5	5.7^{AB}
FB+R	13.2^{B}	31.0^{AB}	19.4^{B}	9.9^{AB}	18.4^{AB}	8.5^{B}	9.8^{B}	6.0^{AB}	3.6	7.0^{AB}
Mean	10.3	25.4	16.6	8.5	15.2	6.2	8.4	5.6	3.5	5.9
Tukey's HSD (P≤0.05)	2.1	4.1	1.9	3.4	NA	1.1	1.3	1.4	1.1	NA

CT: Conventional tillage; PNB: Planting on permanent narrow beds with zero tillage (ZT); PNB+R: PNB with residue retention; PBB: Planting on permanent broad beds with ZT; PBB+R: PBB with residue retention; FB: Planting on flat bed with ZT; FB+R: FB with residue retention; NA: Not applicable. Means followed by same letters within a column are not significantly different at P<0.05 according to Tukey's HSD test.

pre-flowering, flowering, pod filling and harvesting stage, respectively in 0-15 cm of soil depth (Table 1). Continuous residue retention along with zero tillage in different bed system (crop establishment method) increased the NH_4-N content from 6.7 mg/kg (CT) to 15.7 mg/kg (PBB+R) at the pre-flowering stage of crop and this trend was observed in other physiological crop growth stages. The highest concentration of NH_4-N in soil was noticed at the flowering stage, and it was 145% higher than pre-flowering stage of the crop. However, the concentration of NH_4-N in soil decreased at pod filling (16.6 mg/kg) and harvesting stages (8.5 mg/kg) compared to the flowering stage (25.4 mg/kg). Residues of crops have a sufficient amount of C and N that can act as a suitable substrate for soil microorganisms; hence it significantly improved mineralization of N in the soil. In addition to this, CA practices have relatively less soil disturbance in the combination of residue retention, which also stimulated the ammonification process and resulted in increased NH_4-N concentration in CA plots as compared to CT plots. Crop establishment methods (without residue plots) also positively affected NH_4-N concentration in the soil although the effect was marginal in some of the treatment compared to conventional tillage. Between zero tilled without residues retained plots, at pre-flowering and flowering stages, PBB plots recorded the highest NH_4-N concentration, which was 52 and 38% higher than CT plots. The mean NH_4-N concentration of residue retained plots was statistically at par, although it was higher than that of without residue retained and CT plots. Higher concentration of NH_4-N in residue retained plots might be because of residue retention could improve soil's physical properties like structure, temperature etc. (Bhattacharyya *et al.* 2018), which enhanced microorganism metabolism to boost nitrogen mineralization. Lower concentration of NH_4-N at the pre-flowering stage compared to flowering and pod filling stages might be due to immobilization of N during the initial phase of crop residue decomposition.

Like 0-15 cm, residue retention and crop establishment methods significantly impacted NH_4-N concentration of soil at the different growth stages of pigeon pea in 15-30 cm depth. However, the intensity of the effect was less (Table 1). In 15-30 cm of soil depth, NH_4-N concentration in PBB+R plots at different crop growth stage was 177, 102 and 71% higher than CT plots at pre-flowering, flowering, and pod filling stage, respectively. Most importantly, NH_4-N concentration in soil was not significantly altered by crop establishment methods and crop residue retention at the harvesting stage of crop. The average soil NH_4-N concentration increased by 35% from pre-flowering (6.2 mg/kg) to flowering (8.4 mg/kg) and decreased by 33 and 58% respectively, at the pod filling and harvesting stage.

Nitrate nitrogen (NO_3-N): Like NH_4-N concentration, NO_3-N concentration in soil was significantly affected by crop residue retention (Table 2). In general, higher NO_3-N concentration was noticed in PBB+R plots and lower in CT plots irrespective of soil depth and crop growth stages. Among crop residue retained plots, PBB+R at flowering, and pod filling stages recorded significantly higher NO_3-N than others. Among the treatments at various crop growth stages, NO_3-N was highest at the pre-flowering stage (44.2 mg/kg soil) under PBB+R plots, which was 81, 55, 48, 34, 14 and 6%, higher over CT, PNB, FB, PBB, PNB+R and FB+R plots, respectively. It is evident from the data that NO_3-N was 61, 57 and 95% higher in PBB+R plots than CT plots at flowering, pod filling and harvesting stage, respectively.

Maximum mean NO_3-N concentration was noticed at the pre-flowering stage followed by pod filling > flowering > harvest stage in both the depth of soil. At the pre-flowering stage, residue retained PBB, PNB, FB recorded 40, 34, and 35% higher NO_3-N than without residue retained plots with the same crop establishment methods. At the time of pod filling stage, NO_3-N was found highest in treatment PBB+R

Table 2 Nitrate nitrogen (mg/kg soil) concentration in soil at different growth stage of pigeon pea under conservation agriculture

Treatment	Pre-flowering	Flowering	Pod filling	Harvest	Mean	Pre-flowering	Flowering	Pod filling	Harvest	Mean
	0-15 cm					15-30 cm				
CT	24.4^{D}	22.9^{C}	22.8^{D}	13.7^{D}	20.9^{E}	9.4^{B}	7.9^{ABC}	6.3^{D}	4.19	7.0^{C}
PNB	28.5^{CD}	25.5^{BC}	30.6^{C}	18.0^{C}	25.7^{D}	9.2^{B}	7.3^{BC}	7.3^{CD}	4.66	7.1^{BC}
PNB+R	38.6^{AB}	27.9^{B}	36.1^{BC}	23.3^{AB}	31.5^{BC}	10.9^{AB}	8.5^{AB}	9.3^{BC}	4.90	8.4^{ABC}
PBB	32.9^{BC}	26.5^{BC}	33.3^{BC}	21.0^{BC}	28.4^{CD}	8.9^{B}	6.7^{C}	9.1^{BC}	5.72	7.6^{BC}
PBB+R	44.2^{A}	36.9^{A}	43.5^{A}	26.7^{A}	37.8^{A}	12.8^{A}	9.3^{A}	13.5^{A}	5.87	10.4^{A}
FB	29.8^{CD}	26.7^{BC}	30.7^{C}	19.2^{C}	26.6^{D}	9.2^{B}	7.2^{BC}	8.1^{CD}	4.74	7.3^{BC}
FB+R	41.6^{A}	34.6^{A}	39.1^{AB}	24.8^{A}	35.0^{AB}	12.4^{A}	8.8^{AB}	10.4^{B}	5.87	9.3^{AB}
Mean	34.3	28.7	33.7	21.0	29.4	10.4	8.0	9.14	5.14	8.2
Tukey's HSD ($P \leq 0.05$)	6.0	4.6	6.7	3.7	NA	2.3	1.7	2.13	2.41	NA

CT: Conventional tillage; PNB: Planting on permanent narrow beds with zero tillage (ZT); PNB+R: PNB with residue retention; PBB: Planting on permanent broad beds with ZT; PBB+R: PBB with residue retention; FB: Planting on flat bed with ZT; FB+R: FB with residue retention; NA: Not applicable. Means followed by same letters within a column are not significantly different at P<0.05 according to Tukey and it was statistically at par with PNB+R treatment, whereas superior over other treatments. Nitrate nitrogen concentration in soil decreased with an increasing depth. Long-term crop residues retention also increases soil organic matter (Bhattacharyya *et al.* 2018) that could significantly increase the potential of nitrification activity and the abundance of ammonia-oxidizing bacteria (AOB), and ammonia-oxidizing archaea (AOA) (Ai *et al.* 2013). Secondly, adoption of CA practices increased microbial community composition of soil and favored the proliferation of nitrifying microbes that increased nitrification activity. Higher NO_3-N is also related to the preferential oxidation of AOA to ammonia from organic nitrogen (derived from long-term retention of crop residues) mineralization, and AOA possesses a high affinity to ammonia, especially if the ammonia oxidation rate exceeds the mineralization rate. In 15–30 cm of soil depth, the average NO_3-N concentration decreased by 69, 72, 73 and 75% at pre-flowering, flowering, pod filling and harvesting stages, respectively, compared to 0–15 cm soil depth (Table 2). In 15–30 cm soil depth, the mean NO_3-N at different crop growth stage was highest under PBB+R (10.3 mg/kg) plots, which was 49, 46, 42, 37, 23, and 11% higher over CT, PNB, FB, PBB, PNB+R, and FB+R plots, respectively (Table 2). It appears that higher NO_3-N availability at pod filling stages in residues retained plots associated with increased NH_4-N concentration at flowering stage, which stimulated nitrification process, as the requirement of N at this particular crop growth stage is too high. Secondly, the nitrification rate is also controlled by product inhibition concept, which might have favored nitrification activity.

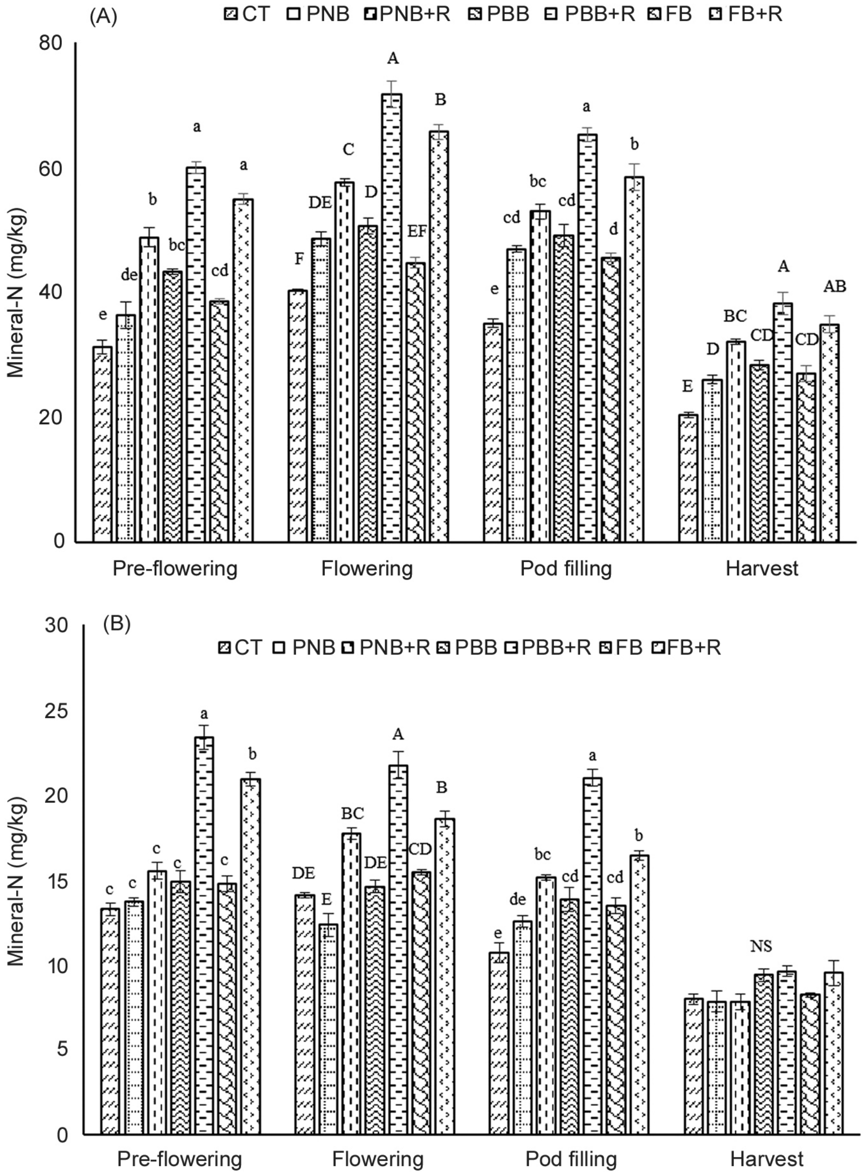

Fig 1 Mineral nitrogen (mg/kg soil) concentration in (A) 0–15 cm and (B) 15–30 cm depth of soil at different growth stage of pigeon pea under conservation agriculture. CT: Conventional tillage; PNB: Planting on permanent narrow beds with zero tillage (ZT); PNB+R: PNB with residue retention; PBB: Planting on permanent broad beds with ZT; PBB+R: PBB with residue retention; FB: Planting on flat bed with ZT; FB+R: FB with residue retention. Bar indicates standard error. Same letters within a stage are not significantly different at P<0.05 according to Tukey's HSD test.

Mineral nitrogen (Mineral-N): Mineral-N accounts for approximately 2% of the total nitrogen in the soil. Soil microorganisms convert organic forms of nitrogen to mineral forms when they decompose organic matter and fresh plant residues. In 0-15 cm soil depth, at pre-flowering stage mineral-N was recorded highest (59.9 N mg/kg soil) under PBB+R treatment, and it was 92, 65, 56, 38, 23, and 9% more than CT, PNB, FB, PBB, PNB+R, and FB+R treatments, respectively (Fig 1A). FB+R, PBB+R, and PNB+R plots recorded 42, 38, and 34% higher mineral-N compared to irrespective without residues retained plots in 0-15 cm of soil depth at pre-flowering stage (Fig 1A). Almost similar trends of mineral-N were recorded at the flowering, pod filling and harvesting stage of the crop. The average mineral-N increased from pre-flowering to flowering and then started decreasing, and the minimum value was recorded at the harvesting stage. Mineral-N of soil decreased with increased soil depth under different crop establishment methods. In 15-30 cm soil depth, the best land configuration at the pre-flowering stage was PBB+R (23.4 N mg/kg soil), and it was 76, 70, 58, 57, 51, and 12 % higher over conventional tillage, PNB, FB, PBB, PNB+R, and FB+R plots, respectively (Fig 1B). In 15-30 cm soil depth, residues' significant positive impact was recorded on mineral-N concentration, but the intensity of impact was less compared to 0-15 cm soil depth. Most importantly, drastic reduction in mineral N was recorded in 15–30 cm, over 0-15 cm soil, and it was 168, 231, 242, and 248% at pre-flowering, flowering, pod filling, and harvest stage, respectively (Fig 1B). Higher mineral-N fractions in residues retained plots might be due to decomposition of residues and further synchronized mineralization. Secondly, the nitrogen fixation capacity of pigeon pea may be higher under residues retained plots because of more congenital soil microenvironment, viz. soil temperature, moisture, extracellular enzymes, etc. (Gomez-Rey *et al.* 2012). Moreover, under conservation tillage, the increased microbial activity observed in the studied soil (Bhattacharyya *et al.* 2018) could facilitate the release of nitrogen, in available forms, from the accumulated plant residues and accumulated organic matter (Sharma *et al.* 2016 and Vishwanath *et al.* 2020). A correlation study revealed that NH_4-N, NO_3-N, and mineral-N at the different crop growth stages were highly correlated with crop yield. Highest correlation coefficient was observed at the pre-flowering stage for NH_4-N (R^2=0.82) and mineral-N (R^2=0.79), whereas harvesting stage for NO_3-N (R^2=0.81) (data not presented).

After 10 years of pigeon pea-wheat crop rotation, conservation tillage resulted in increased NH_4-N, NO_3-N and mineral-N in the soil up to 30 cm of depth. The highest available N fractions (NH_4-N, NO_3-N, and mineral-N) were noticed in PBB+R plots. However, in some of the stages and soil depths, it was statistically similar to other residue retained plots but always superior over ZT without residue retained and CT plots. In pigeon pea crop, the pre-flowering stage and harvesting stage were most appropriate to estimate NH_4-N and NO_3-N respectively; these stages were highly correlated with yield under pigeon pea-wheat cropping system.

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