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Research Article

Effect of Tillage, Residue, Irrigation and Nitrogen Management on Soil Physical Properties and Root Growth Dynamics in Wheat in an Inceptisol

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ABSTRACT

Field experiments were conducted in a sandy loam soil (Typic Haplustept) under a long-term tillage experiment (since 2014) during *rabi* (post-monsoon) season, 2021-22 at the ICAR-IARI experiment farm (MB-4C), New Delhi to study the effect of tillage, residue, irrigation and nitrogen management practices on soil physical properties and root growth in wheat (cv HD 2967). The treatments comprised of two levels of tillage [Conventional tillage (CT) and No tillage (NT) as the 1st main plot], two levels of residue mulching [maize crop residue mulch @ 5t ha^{-1} (R+) and without residue (R0)] as 2nd main-plot factors and three N doses (50, 100 and 150% of the recommended dose of N) and two levels of irrigation [full irrigation (I_F) and deficit irrigation (I_D)] as subplot factors, in a split-factorial plot design with three replications. Results showed an increase in mean weight diameter (MWD) at 0-5, 5-15, and 15-30 cm soil depths under the NT, and crop residue mulching compared to CT and no residue. With the increase in nitrogen doses, the MWD of soil increased in all these layers. There was a decrease in bulk density (BD) and an increase in soil hydraulic conductivity (SHC) of soil under NT and residue mulching. The root length density (RLD), root mass density (RMD), and root diameter (RD) of wheat increased under the NT. Adoption of the long-term NT system with maize residue as mulch can lead to better soil physical conditions and root growth, contributing in the growth and yields of irrigated wheat in the Indo-Gangetic Plains region.

Keywords: Mean weight diameter, Root length density, Root mass density, Meta-analysis, Conservation tillage

Introduction

Tillage methods influence wettability, water extraction pattern, and transport of water and solutes through the soil profile by modification of soil structure, aggregation, total porosity, and pore size distribution (Lindstrom and Onstad, 1984). It often affects root development and function, which by far is the most important component in crop growth (Mosaddeghi *et al.*, 2009). Root morphology and spatial distribution are significantly affected by soil properties (Linkohr *et al.*, 2002). A higher soil bulk density and subsurface mechanical impedance can decrease root length and trigger the formation of lateral roots (Ball Coelho *et al.*, 1998). Physical properties of soil such as bulk density (BD),

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aggregate size, and stability strongly influence the root size and its profile distribution by affecting the relation between void and filled-up pore spaces and thus changing the degree of aeration in soil, indirectly influencing root growth (Ball *et al.*, 2005). Therefore, the coordination of root system distribution, and available soil moisture in the soil profile, is required for optimal plant growth and production (Vanessa *et al.*, 2013). Soil physical limitations– mainly mechanical impedance, hypoxia, water stress, and non-optimal temperature – represent a significant restriction to root system growth in many soils (Bengough *et al.*, 2006), which are influenced by tillage practices.

Conservation tillage practices such as no-till with residue retention are a practical means to enhance crop productivity and resource use efficiency for rainfed ecosystems (Amgain *et al.*, 2019). NT practices result in the reduction of runoff and soil erosion loss, alleviation of soil phosphorus pollution, enhancement of soil organic carbon sequestration, and increase in soil moisture storage (Lal, 2004; Soane *et al.*, 2012). Intensive tillage practices like Conventional tillage (CT) disrupt soil aggregates, increasing their erodibility, and runoff loss (Dwyer *et al.*, 1996), causing mechanical impedance (Cox *et al.*, 1990) and macropore discontinuity (Rosenberg and McCoy, 1992; Shipitalo *et al.*, 2000), and modification of hydrothermal regimes (Cox *et al.*, 1990; Fuentes *et al.*, 2003). Fuentes *et al.* (2004) and Hu *et al.* (2009) observed that hydraulic properties change due to temporal changes in surface properties, which could be an outcome of the tillage practices involved. This affects rooting depth, root architecture, and root distribution (Dwyer *et al.*, 1996) leading to a reduction in water and nutrient uptake causing unsustainable production and reduced resource use efficiency. Zhang *et al.* (2006) noted augmentation in soil tilth for no-tillage beyond sowing depth promoting better root growth and root architecture development.

Although root growth as influenced by tillage, crop residue mulching, nutrient level, and irrigation management has been studied in isolation there is very limited study on the interaction of these management practices on root growth and input use efficiency of wheat. No single complete study encompassing the tillage-residue-water-N induced modifications on macro- (bulk density and hydraulic conductivity) and micro (soil aggregates) scale changes in soil physical condition and their impact on root-growth in wheat has yet to be reported. It was hypothesized that no-tillage and crop residue mulching under an optimal combination of water and nutrient management would enhance soil physical conditions and improve root growth in wheat. To test this hypothesis, the present investigation was undertaken to study the effect of tillage, crop residue mulching, irrigation, and nitrogen levels on soil physical properties and root growth of wheat and also a global meta-analysis was undertaken on soil physical properties and root growth of wheat under maize-wheat cropping system.

Materials and methods

Weather and soil

Field experiments were conducted in the MB-4C farm of ICAR-Indian Agricultural Research Institute, New Delhi (28°35′ N latitude, 77°12′ E longitude and at an altitude of 228.16 m above mean sea level) with wheat (cv. HD2967) as a test crop during the year 2021-2022 in an ongoing tillage experiment on maize-wheat cropping system continuing since 2014. The soil of the MB-4C farm was sandy loam (Typic Haplustept) of Gangetic alluvial origin, flat, well-drained and very deep (>2 m). Detailed soil physical and chemical characteristics before starting the experiment are presented in Table 1. The monthly average maximum and minimum temperature, maximum and minimum relative humidity, bright sunshine hours, rainfall, evapor-ation, and wind speed during the crop growth periods of wheat for 2021-22 and 30-years normal weather data is presented in Table 2.

Treatment details

The treatments were replicated thrice under a split-factorial plot design with two levels of tillage [Conventional tillage (CT) and No tillage (NT)] and, two levels of residue mulching [maize crop residue mulch @ 5t ha^{-1} (R+) and without residue (R0)] as main-plot factors and three N doses (50, 100 and 150% of the recommended dose of N) and two levels

Table 1. Physicochemical properties of the soil at the experimental site

Depth (cm)	Bulk density (Mg/m^3)	pH	EC ($dS\ m^{-1}$)	Saturated hydraulic conductivity ($cm\ h^{-1}$)	SOC (g/kg)	Particle size distribution			Soil texture	Soil moisture constants (cm^3/cm^3)	
						Sand (%)	Clay (%)	Silt (%)		0.033 MPa	1.5 MPa
0-15	1.58	7.1	0.46	1.01	4.2	64.0	16.8	19.2	SL	0.254	0.101
15-30	1.61	7.2	0.24	0.82	2.2	64.4	10.7	24.9	SCL	0.269	0.112
30-60	1.64	7.5	0.25	0.71	1.6	63.8	10.0	26.2	SCL	0.283	0.129
60-90	1.71	7.5	0.25	0.49	1.2	59.8	10.0	30.2	SCL	0.277	0.110
90-120	1.72	7.7	0.3	0.39	1.1	53.7	13.4	32.9	SCL	0.247	0.097

of irrigation [full irrigation (I_F) and deficit irrigation (I_D)] as subplot factors. Three levels of nitrogen include 50% (N60), 100% (N120) and 150% (N180) of the recommended dose of nitrogen in wheat corresponding to 60, 120 and 180 kg N/ha, respectively. Two levels of irrigation include I_D (Deficit irrigation) i.e., three irrigations at CRI (21 DAS), jointing (65 DAS), milking (105 DAS) and I_F (Full irrigation) i.e., five irrigations at CRI (21DAS), tillering (45 DAS), jointing (65DAS), flowering (85DAS), milking (115 DAS) stages. The depth of irrigation was ~6 cm. The layout of the experiment is presented in Fig. 1.

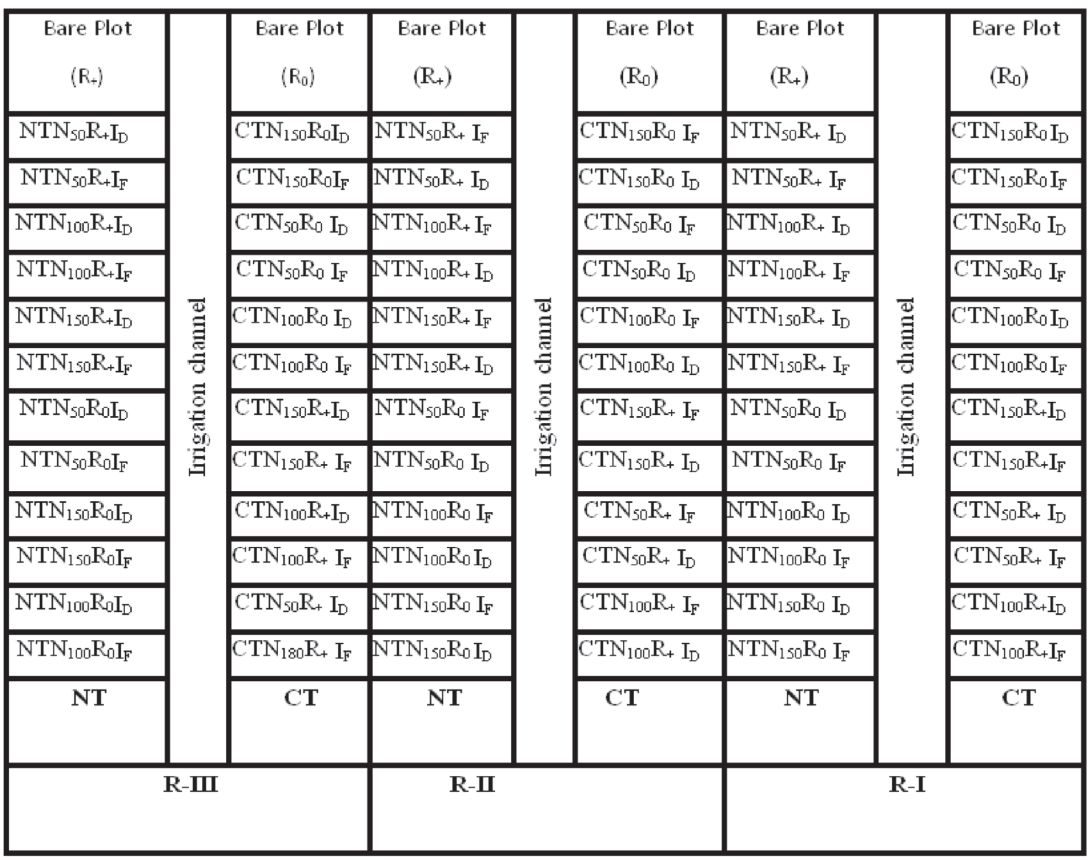


Fig 1. Layout of the Field Experiment

CT: Conventional tillage, NT: No tillage, R_0: No mulch, R_+: With crop residue mulch @ 5t/ha, $N_{50\%}$: 50% of recommended dose of N, $N_{100\%}$: 100% of recommended dose of N, $N_{150\%}$: 150% of recommended dose of N, I_D: Deficit irrigation (3 critical stages), I_F: Full irrigation (5 Critical stages)

Table 2. Monthly weather condition during wheat growth during the year 2021-22 and Normal weather

Month	Max. Temp. (°C)		Min. Temp. (°C)		Max. RH (%)		Min. RH (%)		Sunshine hours		Rainfall (mm)		Evaporation (mm)		Wind speed (km/h)	
	2021-22	Normal	2021-22	Normal	2021-22	Normal	2021-22	Normal	2021-22	Normal	2021-22	Normal	2021-22	Normal	2021-22	Normal
November	27.1	28.0	10.6	11.4	91.6	86.1	52.0	37.8	4.5	6.2	0.0	4.9	2.5	3.0	1.6	1.9
December	21.9	22.5	7.3	7.0	90.6	90.2	64.2	45.9	3.7	4.5	6.0	8.0	1.8	2.4	2.0	2.4
January	17.4	19.8	7.4	6.4	92.3	91.7	75.7	52.1	2.4	5.2	141.9	16.6	1.6	2.0	3.2	3.2
February	23.1	23.3	8.7	9.1	89.6	88.4	51.6	45.8	6.5	6.8	30.0	18.9	2.8	3.1	4.1	4.0
March	32.4	29.2	15.3	13.6	80.2	80.4	39.0	37.4	8.2	7.8	0.0	14.3	4.6	5.1	3.9	4.3
April	40.2	36.1	19.9	19.1	65.1	63.2	15.0	29.0	8.7	8.6	0.0	12.1	6.8	8.0	4.1	4.7

Wheat crop (cv. HD 2967) was sown on 23rd November 2021 by a tractor-drawn no-till seed drill (at a depth of 4-5 cm) with a row spacing of 22.5 cm at a seed rate of 100 kg ha^{-1} and harvested on 17th April 2022. Plots under CT treatment were ploughed once with a disc plough and once with a duck-foot tine cultivator followed by levelling and sowing by seed drill. The seed was directly sown in NT treatment using an inverted T type no-till seed drill. Maize residue was applied manually at the rate of 5 t ha^{-1} under R+ treatment at the CRI stage. Similarly, during *kharif* season, wheat residues were applied to the standing maize crop at the rate of 5 t ha^{-1} under R+ treatment. Nitrogen was supplied as urea in three splits i.e., 50% at sowing, 25% at CRI stage and the remaining 25% at the flowering stage. The field was kept weed free by employing manual weeding 3-4 times during crop growth stages.

Soil physical properties

Undisturbed soil sample was collected using core sampler before sowing of the wheat crop at 0-15 and 15-30 cm soil depth for the analysis of bulk density and saturated hydraulic conductivity. Similarly undisturbed soil samples were collected from 0-5, 5-15 and 15-30 cm soil depth using core samplers for soil aggregate analysis.

i. Bulk density and porosity

Bulk density (BD) was determined by core method. Total porosity was determined as

$$P_t = (1\text{-}BD/PD) \times 100 \qquad \ldots(1)$$

In which, BD = Bulk density: PD = Particle density of soil (taken as 2.65 Mg m^{-3} for mineral soils)

ii. Soil aggregate analysis

The aggregate size distribution for aggregates of 2-8 mm sizes at three depths i.e., 0-5 cm, 5-15 cm, and 15-30 cm depths were analysed by wet-sieving method with the help of Yoder's wet sieve apparatus (Yoder, 1936). The percentage of water-stable aggregates (> 250 µm diameter) was measured and the mean weight diameter was calculated (Van Bavel, 1949) from the weighted mean of aggregate retained in each sieve by using the formula:

$$MWD = \left(\sum_i^n xi \times wi\right) \quad \ldots(2)$$

where, the mean diameter of the sieve size class (mm) is given by x_i and w_i is the proportion of the weight of soil samples retained on each sieve.

iii. Saturated hydraulic conductivity

Undisturbed soil samples collected from the fields from 0-15 and 15-30 cm depth using soil cores (with 5 cm internal diameter and 6 cm height) to determine the saturated hydraulic conductivity (Ksat) with the help of Constant Head Permeameter (Klute, 1986).

Saturated hydraulic conductivity of the soil cores was calculated using Darcy's equation:

$$K_{sat} = (Q/At) \times (L/H) \quad \ldots(3)$$

Q is the amount of water passing (cm^3) through the core, t is the time (h), Q/At is the water flux, and L is the length of the core and H is the total hydraulic head and H/L is the hydraulic head gradient.

Root growth dynamics

Root analysis was performed at four critical growth stages (CRI, Flowering, Milking and Maturity) using Winrhizo software. After removing of above-ground biomass, root sampling was done using a root auger of dimensions (7.5 cm diameter and 60 cm height). The core of the auger was placed to center the base of the stem and the soil core was excavated at 0-15 cm and 15-30 cm soil depths. Then the roots and their corresponding adhered soil mass were sealed in polythene bags till preliminary washing by running water over sieves. Further washing was done thoroughly till no soil mass was visible on the root surfaces. The clean samples were now sealed and refrigerated till further analysis. The root lengths, surface area, average diameter, and volume were recorded using WINRHIZO Software (WINRHIZO system, Regent Instruments Inc., Canada) by scanning and analysing the root images. After scanning, root samples were collected in an envelope and dried in an oven at 60 °C till constant weight was achieved. After that, Root Length Density and Root Mass Density were calculated by dividing root lengths and oven dried root mass by core volume respectively (Chakraborty *et al.*, 2008; Bandyopadhyay *et al.*, 2010).

Root extension rate was computed as:

$$RER = (RLD_n - RLD_{n-1})/(t_n - t_{n-1}) \quad \ldots(4)$$

Where, RLD_n and RLD_{n-1} are root length densities at t_n and t_{n-1} days

Meta-analysis of soil physical properties, root growth, yield and water use efficiency under different tillage practices

Data extraction from peer-reviewed publications (2000-2021) investigating the effects of no-tillage vis-a-vis the conventional tillage practice on soil physical properties and root growth were searched in 'Scopus' database "'Soil' AND 'Root' AND 'Wheat' AND 'Maize'" in the article title, abstract and keywords.

A selection of 297 data points from 26 studies were subjected to a meta-analysis of four major soil physical parameters e.g. (a) soil bulk density, BD (Mg m^{-3}), (b) mean weight diameter of soil aggregates, MWD (mm), (c) Aggregate stability (%). In addition, root growth parameters considered were root length density (RLD), root mass density (RMD), and root diameter (RD). Care was taken to extract data from each study so that these are consistent to one another. All data pertained to wheat crop under the maize-wheat cropping system were used.

Database preparation

Effect sizes from individual studies were combined using a random-effects model, and was considered significant if the 95% confidence intervals (CIs) [Mean ± 1.96 * SD/Sqrt (number of observations); 1.96 is the 'z'-value at 95%] did not overlap with zero. Meta-analysis was also performed for the maize-wheat cropping system. The between-study variability (heterogeneity) was evaluated through standard chi-squared test (Cochran's Q-statistic; Cochran, 1954), the I^2 statistic (Higgins *et al.*, 2003), and Tau-squared. A statistically significant ($p<0.05$) Cochran Q-test proved heterogeneity. The I^2 statistic described the percentage of variation in effect size estimates, which were due to heterogeneity rather than by chance (Deeks *et al*., 2008). $I^2> 75\%$ was considered for true heterogeneity. The Tau-squared implied the variance (heterogeneity) of the true effect sizes. The 'metafor' package (Viechtbauer, 2010) in the R statistical computing platform (R Core Team, 2017) was used, and significant changes were reported at p<0.05 or p<0.01. Publication bias was assessed through histograms (Rosenberg *et al*., 2000) and none of the cases, effect sizes showed preferences towards positive or negative bias.

Statistical analysis

Analysis of variance (ANOVA) for split-factorial design was performed for all the dataset using SAS software. To determine the significance of treatment effects F-test and to analyse the difference between the means, the least significance difference at 5% probability level was performed.

Results and Discussion

Weather

It was observed that the crop experienced higher maximum temperature during the month of March and April by 3.2 °C and 4.1°C, respectively over the normal, which coincides with the maturity period. Even the minimum temperature was higher by 1.7°C and 0.8°C as compared to normal during January, March, and April, respectively. During 2021-22, the crop received a total rainfall of 177.9 mm as against 74.8 mm reported in the normal weather. In the month of January 141.9 mm rainfall was received. The average sunshine hours for 2021-22 was 5.7 h against the normal 6.5 h. The mean relative humidity observed during 2021-22 (67.2%) was higher than normal weather (62.3%)

Bulk Density, Porosity, Saturated hydraulic conductivity and Mean weight diameter

Bulk density at 0-15 and 15-30 cm soil depth after harvest of wheat 2021-22 as influenced by tillage, crop residue mulch and nitrogen management is depicted in Fig. 2. The average bulk density of soil at 0-15 and 15-30 cm soil depth were 1.47 and 1.53 Mg m^{-3}, respectively. It was observed that BD decreased by 2.0% and 1.5% at 0-15 and 15-30 cm soil depths, respectively under NT as compared to CT. The effect of crop residue mulch was not significant on BD. However, with an increase in nitrogen level, BD decreased in all four depths due to increased root growth and formation of biopores (Hati *et al.*, 2015).

The total porosity as influenced by tillage, residue and nitrogen management are depicted in Fig. 3. The average total porosity of soil at 0-15 and 15-30 cm soil depth was 44.6 and 40.3%, respectively. Under NT, total porosity at 0-15 and 15-30 cm soil depths increased by 1.1 and 0.9 % compared to CT. Under crop residue mulch, total porosity at 0-15 and 15-30 cm soil depths increased by 2.8 and 2.3 % compared to no mulch due to better soil aggregation under crop mulch (Bag *et al.*, 2020). With the increase in N dose, the total porosity increased at both 0-15 cm and 15-30 cm soil depths.

The average saturated hydraulic conductivity (SHC) at 0-15 cm and 15-30 cm soil depth were1.81 and 1.63 cm hr^{-1}, respectively (Fig. 3). SHC under NT at 0-15 and 15-30 cm depth was higher than CT by 6.7 and 7.8 % due to higher porosity, in the

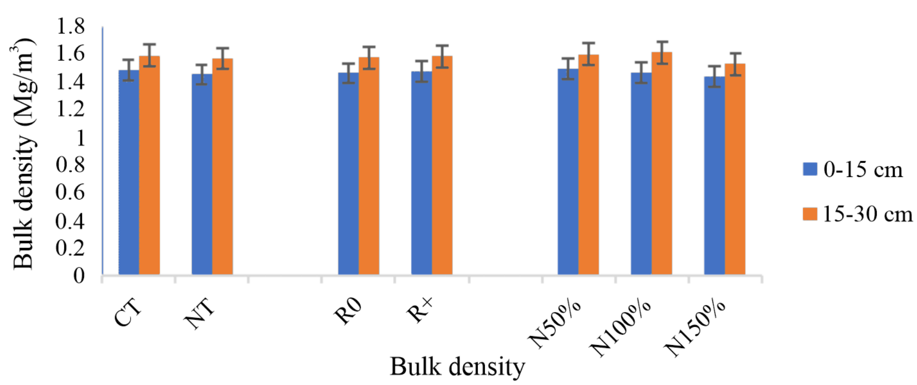


Fig. 2. Soil bulk density at 0-15 and 15-30 cm as influenced by tillage, crop residue mulching and Nitrogen management

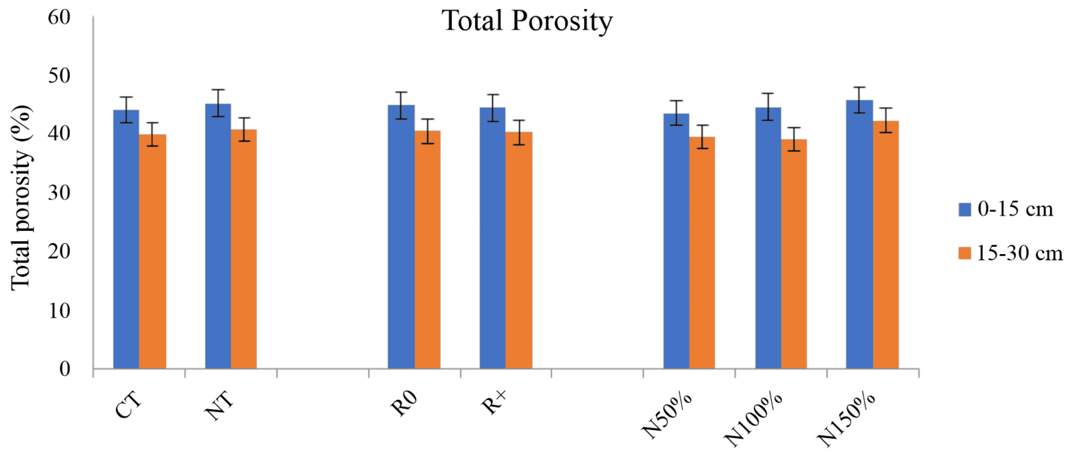


Fig. 3. Total porosity at 0-15 and 15-30 cm as influenced by tillage, crop residue mulching and Nitrogen management

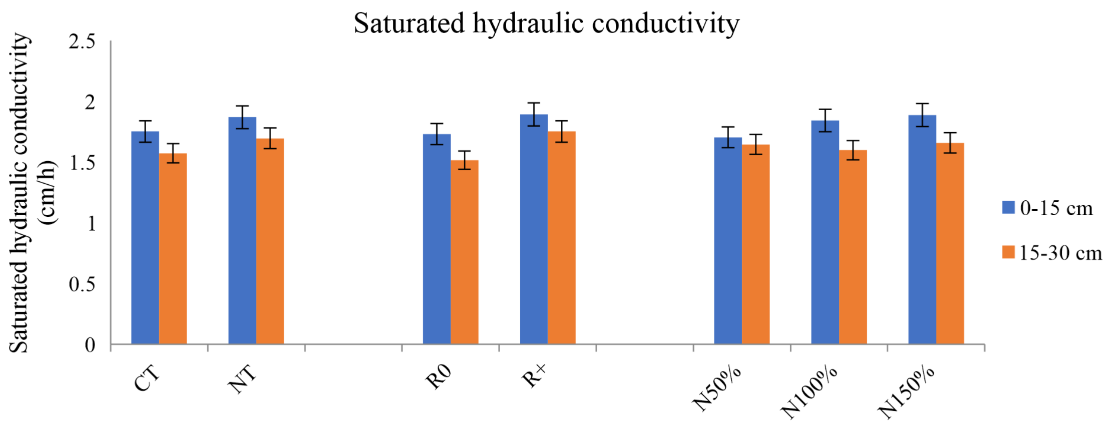
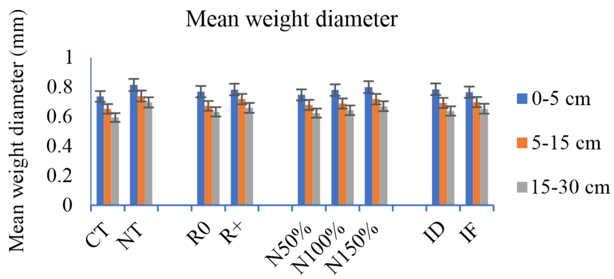


Fig. 4. Saturated hydraulic conductivity at 0-15, 15-30 cm soil depth as influenced by tillage, crop residue mulching and nitrogen management

presence of preferential flow paths and possibly due to higher earthworm activities (Moreno *et al.*,1997).

However, Six *et al.* (1998) explained the lower saturated hydraulic conductivity under CT due to tillage-induced mechanical breakdown of aggregates further leading to structural degradation of the CT plots. Due to crop residue mulch, there was a significant increase in SHC by 9.3 and 15.6 % over no-mulch at 0-15 and 15-30 cm depths, respectively due to the improvement in soil structure under crop residue mulch and higher porosity under crop residue mulch (Six *et al.*, 2000) and (Acharya *et al.*, 2005). The application of a higher nitrogen dose led to an increase in SHC at these depths.

Mean weight diameter (MWD) and water stable aggregates percentage (%WSA) as influenced by tillage, residue mulch and nitrogen management at 0-5, 5-15 and 15-30 cm are depicted in Fig.5. Mean values of MWD were 0.77, 0.69 and 0.64 mm at 0-5, 5-15 cm and 15-30 cm soil depths respectively. Under NT, MWD was higher than CT by 10.5, 13.4 and 7.3% at 0-5, 5-15 and 15-30 cm soil depths, respectively. Crop residue mulch resulted in increase of MWD by 1.8, 6.8 and 4.4% at 0-5, 5-15 and 15-30 cm soil depths, respectively, which could be attributed to the fact that rainfall impact is absorbed by crop mulch preventing surface crusting (Baumhardt and Lascano, 1996), reducing the splashing effect of rain and improving overall aggregate stability (Six *et al.*, 2000). With increase in N level, a higher MWD was reported possibly due to more root and shoot growth promoting better soil aggregation.



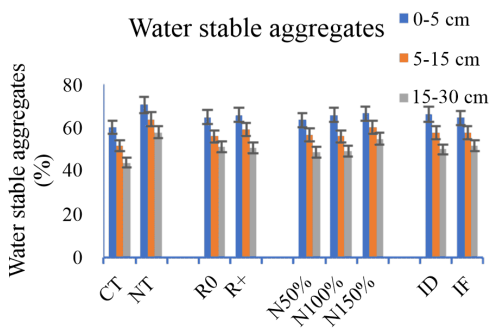


Fig 5. Mean weight diameter and water stable aggregate of soil at 0-5, 5-15 and 15-30 cm soil depth as influenced by tillage, crop residue mulching and nitrogen management

An increase in % WSA , was noted under crop residue mulch by 1.2 and 3.2% over no-mulch, at 0-5 and 5-15 cm soil depths, respectively though the effect was statistically similar. With increase in nitrogen level, there was significant increase in %WSA at 0-5, 5-15 and 15-30 cm soil depths but the effect of irrigation on %WSA was not statistically significant.

Global meta-analysis of soil physical properties under conventional tillage and no tillage with maize-wheat cropping system

Global meta-analysis of soil physical properties as influenced by conventional tillage and no tillage under maize-wheat cropping system was carried out to assess the effect of these tillage treatments on diverse soil and agroclimatic environment across the globe and to compare the result of this meta-analysis with the results obtained from the current field experiment. The global meta-analysis validation statistics for the soil physical properties viz., BD, MWD and WSA is presented in Table 3 and the meta-analysis results of soil physical parameters under maize-wheat system like BD, MWD and WSA is depicted in Fig.6. Although there was increase in MWD and decrease in B.D. under NT as compared to CT, the effect was not statistically significant. However, there was significant increase in % WSA under NT compared to CT at the surface 0-15 cm soil depth. This finding is in agreement with the present study.

Root growth under conventional tillage vis-à-vis no tillage

Root length density (RLD), root mass density (RMD) and root diameter (RD) of wheat as influenced by tillage, residue, irrigation and nitrogen management at CRI, Jointing, Flowering and Milking stages are depicted in Fig.7. Average RLD at 0-15 and 15-30 cm soil depth were 1.231 and 0.590 cm cm^{-3} at flowering. Averaged over residue, nitrogen and irrigation RLD under NT was significantly higher compared to CT by 89.2, 51.8, 21.9 and 23.3% for 0-15 cm at CRI, jointing, flowering and milking stages, respectively which could be due to better soil aggregates, soil porosity and lower BD recorded under NT than that of CT (You *et al.*, 2017) resulting in better availability of nutrients to the root under NT (Piccoli *et al.*, 2021). RLD increased significantly at 0-15 and 15-30 cm soil depths with increase in nitrogen level. Again, under full irrigation (I_F) significant increase in RLD was found over deficit irrigation (I_D) by 21.3 and 15.5% at 0-15 cm soil depth during flowering and milking stages, respectively.

Table 3. Meta-analysis validation statistics for the soil physical parameters under study

Soil layer	Mean weight diameter (mm)			Aggregate stability			Bulk density		
(cm)	I^2	Q stat	p	I^2	Q stat	p	I^2	Q stat	p
0-15	0	1.3249	0.2803	98.53	477.5629	<0.0001	0	0.2923	0.8683
15-30	0	0.3235	0.7963	0	0.6929	0.6921	0	0.1287	0.9483
30-45	0	0.0001	0.9942				0	0.0683	0.7938

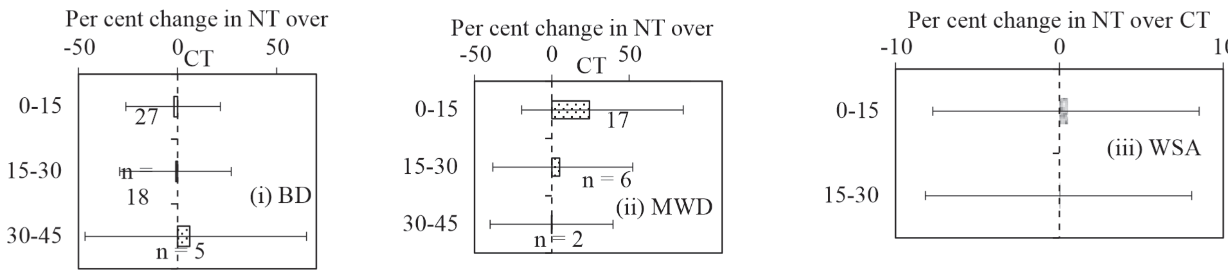


Fig. 6. Meta-analysis of soil physical properties viz., (i) BD, (ii) MWD and (iii) WSA under NT vs CT treatments

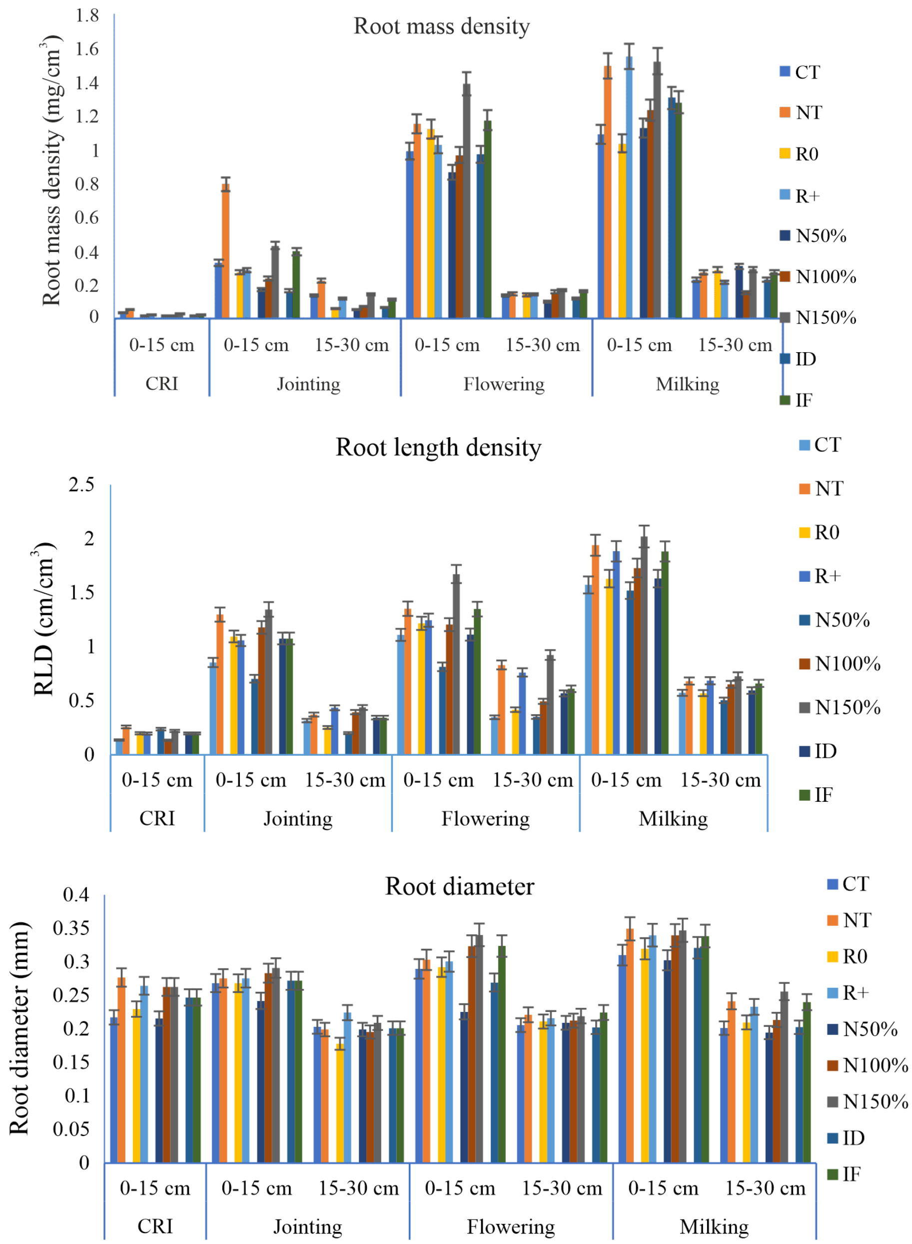


Fig. 7. Root length density, root mass density and root diameter of wheat at CRI, jointing, flowering and milking stage as influenced by tillage, crop residue mulching, nitrogen and irrigation management

The mean RMD at 0-15 cm soil depth was 0.045, 0.563, 1.078 and 1.294 mg cm^{-3} at CRI , jointing, flowering and milking stages, respectively. Under NT, RMD at 0-15 cm was significantly higher than CT by 41.1, 140.2, 16.2 and 37.4% at CRI, jointing, flowering and milking stages respectively. Under crop residue mulch, RMD at 0-15 cm significantly improved over no mulching by 32.1 and 39.6% at CRI and milking stages whereas at 15-30 cm soil depth, it increased only at jointing stage by 88.2% over no mulch. Under $RDN_{150\%}$, RMD significantly improved by 37.2 and 54.6% compared to $RDN_{100\%}$ and $RDN_{50\%}$ application at 0-15 cm soil depths, respectively. Similarly, for 15-30 cm soil depth, under $RDN_{150\%}$ RMD was higher by 58.1% and 30.5% over $RDN_{100\%}$ and $RDN_{50\%,}$ respectively. Under I_F, there was significant increase in RMD by 41.1, 140.2 and 20.7% at CRI, Jointing and flowering stages as compared to $I_{D.}$ was observed at 0-15 cm soil depth. Similarly at 15-30 cm soil depth, under full irrigation it was higher by 60.4, 33.2 and18 % at jointing, flowering and milking stages, respectively compared to deficit irrigated plots. This shows that under NT with crop residue mulching and at higher nitrogen and water availability the RMD increased at 0-15 cm soil depth.

NT resulted in significantly higher RD compared to CT at 0-15 cm soil depth by 27.8 and 12.7% at CRI and Milking stages, respectively. Again, at 15-30 cm soil depth, only at the milking stage, NT was observed to register higher RD by 19.8% over CT. This finding matched with observations reported by Qin *et al.* (2004) and You *et al.* (2017). Crop residue mulch led to significantly higher RD by 15.1% at CRI and by 6.3% at milking stages for the 0-15 cm soil depths. With the application of higher levels of nitrogen there was increase in RD. It was observed that $RDN_{150\%}$ resulted in significantly higher RD by 25.9% over $RDN_{50\%}$ at 0-15 cm soil depth whereas RD under $RDN_{100\%}$ and $RDN_{50\%}$ were found to be statistically at par with each other. Under full irrigation, RD at 0-15 cm was found to be 20.3% more at flowering and 5.5% more at milking stages and at the 15-30 cm soil depths, RD was higher by 11% at flowering and 18.4% at milking compared to $I_{D.}$.

It was observed that mean root extension rate at 0-15 cm soil depth was maximum at 90-105 DAS whereas at 15-30 soil depth it was higher than at 71-90 DAS. Under NT and crop mulching, at 90-105 DAS, there was increase in root extension rate at 0-15 cm soil depth but decrease in the 15-30 cm soil depth as compared to CT and no-mulch, respectively (Fig. 8). Again, with increase in nitrogen levels, there was decrease in root extension rate at 90-105 DAS both for 0-15 and 15-30 cm soil depths, however with increase in irrigation application, it increased significantly for both the soil depths.

Global meta-analysis of root growth of wheat under conventional tillage and no tillage in maize-wheat cropping system

Global meta-analysis performed on root growth parameters (Fig. 9) under differential tillage practices showed that there was significant increase in RLD at 0-15 cm in NT ($p<0.0001$) as compared to CT. This result is in agreement with that of the present field experiment. Further at 45-60 cm there was significantly higher RLD under NT compared to CT ($p=0.0274$). Though there was increase in RMD at 0-15, 15-30, 30-45 and 45-60cm soil depths, the effect was not statistically significant.

Correlation between soil physical properties and root growth of wheat

Correlation matrix between RLD at 0-15 cm soil depth, and the MWD (mean weight diameter) and WSA (water stable aggregate), BD (Bulk Density) and SHC (soil hydraulic conductivity) is presented in Table 4. It was observed that RLD for the same depth, at CRI was significantly positively correlated with MWD (r=0.60*) and WSA (r=0.70*). Again, at same depth, RLD at jointing stage was positively correlated with MWD (r=0.75*), WSA (r=0.72**) and SHC (r=0.60*), but negatively correlated with BD (r= -0.85**). At milking stage, RLD at 0-15 cm soil depth was significantly and positively correlated with MWD (r= 0.79**), WSA (r=0.77**) and SHC (r= 0.70*), but showed negative correlation with BD (r= -0.60*). During the same stage, RLD at 15-30 cm soil depth showed significant positive correlation with MWD (r=0.59*), WSA(r=0.59*), however, at this depth correlation of RLD with any of the soil physical parameters were found to be non-significant.

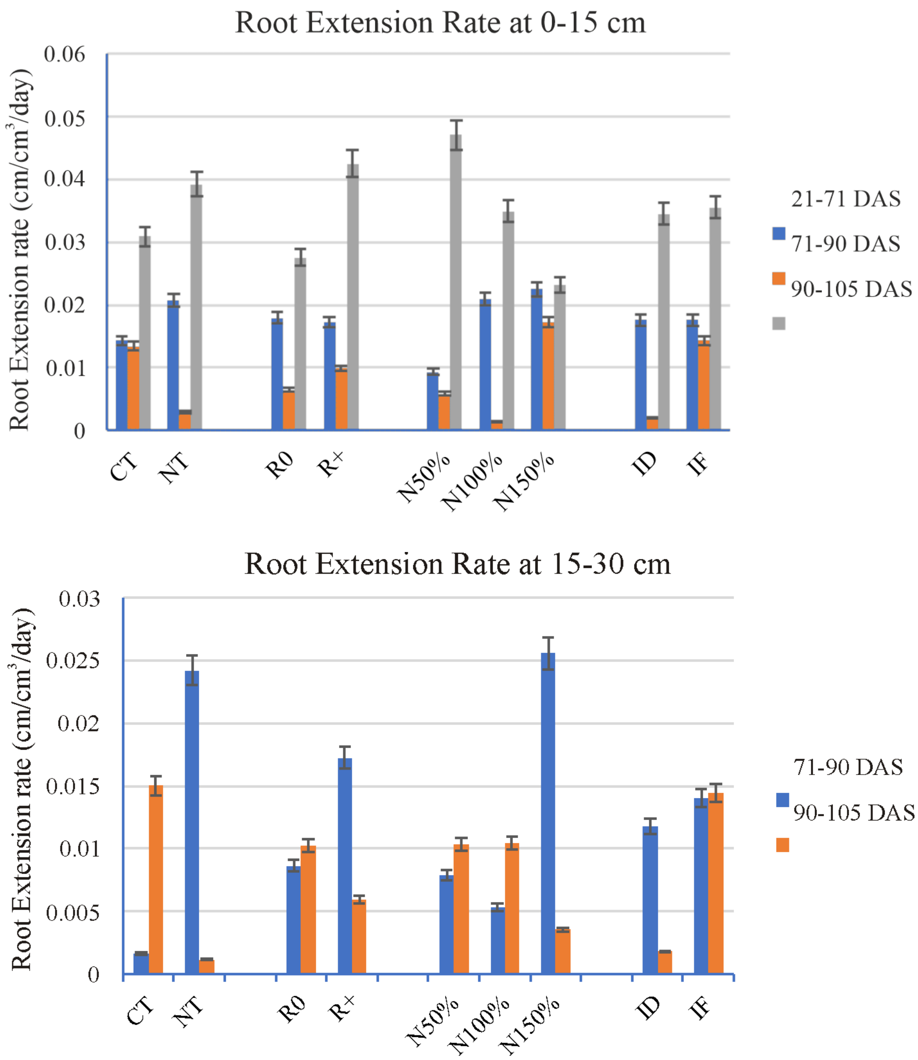


Fig. 8. Root extension rate at 0-15 and 15-30 cm soil depth as influenced by tillage, crop residue mulching and nitrogen level

Table 4. Correlation matrix between root length density of wheat and soil physical properties at 0-15 cm soil depth

	MWD_ 0-15 cm	WSA_ 0-15 cm	BD_ 0-15 cm	SHC_ 0-15 cm	CRI RLD_ 0-15 cm	Jointing RLD _0-15 cm	Flowering RLD_ 0-15 cm	Milking RLD_ 0-15 cm
MWD_0-15 cm	1.00							
WSA_0-15 cm	0.93**	1.00						
BD_0-15 cm	-0.61*	-0.51	1.00					
SHC_0-15 cm	0.67*	0.55	-0.36	1.00				
CRI RLD_0-15 cm	0.60*	0.70*	-0.32	-0.01	1.00			
Jointing RLD_0-15 cm	0.75**	0.72**	-0.70*	0.60*	0.29	1.00		
Flowering RLD_0-15 cm	0.60*	0.43	-0.85**	0.55	0.22	0.78**	1.00	
Milking RLD_0-15 cm	0.79**	0.77**	-0.60*	0.70*	0.45	0.74**	0.69*	1.00

* Significant at $p < 0.05$; ** Significant at $p < 0.01$

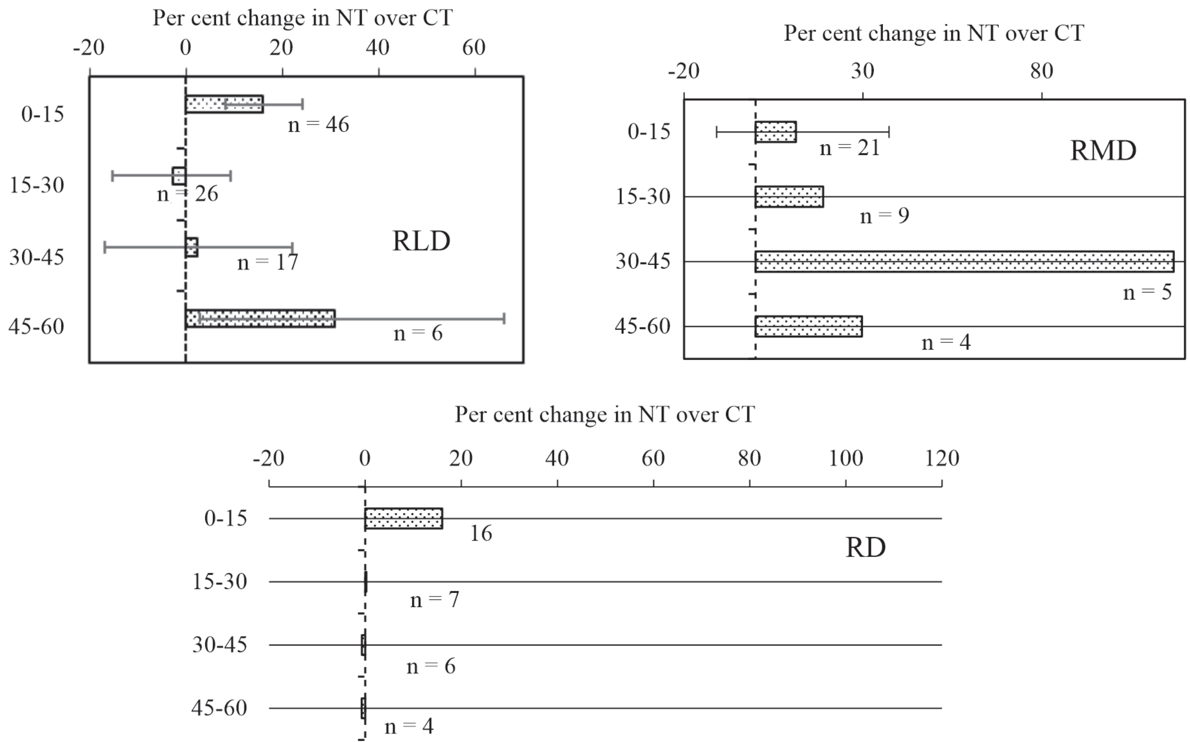


Fig. 9. Meta-analysis root growth properties viz., (i) RLD, (ii) RMD and (iii) RD under NT vs CT treatments

Conclusions

The study showed an increase in mean weight diameter (MWD) at 0-5, 5-15 and 15-30 cm, soil depths under NT and crop residue mulching than CT and no mulch, respectively. With increase in nitrogen, the MWD of soil increased in these depths. There was decrease in BD and increase in saturated hydraulic conductivity (SHC) of soil under NT and crop residue mulching. There was increase in root length density, root mass density and root diameter of wheat under NT than that of CT. The improvement in soil physical properties under NT improved the root growth of wheat as evidenced by the correlation studies. The correlation studies showed that root length density of wheat was significantly positively correlated with MWD and WSA but negatively correlated with the BD of soil at 0-15 cm soil depth. The results from this study followed the similar trend as the global meta-analysis of soil physical properties and root growth of wheat in maize-wheat cropping system. Therefore, wheat may be grown under NT with crop residue mulching and 100% RDN and five irrigations to improve soil physical health and root growth of wheat, in sandy loam soils of IGP region.

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