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Influence of Irrigation, Crop Residue Mulch and Nitrogen Management Practices on Soil Physical Quality

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Improvement in soil structure is a prerequisite for maintaining soil physical health/quality and for sustaining agricultural productivity at higher level. Field experiments were conducted during the *kharif* season of 2012 and 2013 on maize crop in a sandy loam soil to study the impact of different management practices *viz.*, irrigation, crop residue mulch and nitrogen (N) fertilization on soil physical quality indices like least limiting water range (LLWR), *S* index, mean weight diameter (MWD), water stable aggregates (%WSA) and whole soil stability index (WSSI), and their impact on crop growth and yield. Maize (*cv* HQPM 1) was grown in a split-split plot design with two levels of irrigation (irrigated and rainfed), two levels of mulch (no mulch and wheat residue mulch @ 10 t ha^{-1}) and three levels of N (0, 75 and 150 kg N ha^{-1}). Soil physical quality parameters such as *S* index, LLWR, MWD, %WSA and WSSI increased due to irrigation, crop residue mulching and N application. Application of irrigation, mulch and N @ 150 kg ha^{-1} significantly increased the *S* index by 3.5, 9.9 and 4.3 per cent, respectively compared to the respective control treatments (rainfed, no mulch and no N treatments). Crop residue mulching significantly increased LLWR by 48.3, 11.4 and 31.6 per cent over no-mulch treatment at 0-15 cm soil depth at 67 days after sowing (DAS), 95 DAS and harvest, respectively. Application of irrigation registered significantly higher MWD by 21.4 per cent after maize harvest over the rainfed treatment, whereas, mulching increased MWD by 6.7 per cent after maize harvest than no-mulch treatment. After maize harvest, mulching registered significantly higher WSA by 7.8 per cent over the no-mulch treatment. The root growth, grain and biomass yield of maize was significantly correlated with the saturated hydraulic conductivity of soil at 0-15 cm soil depth. Therefore, growing maize crop with need based irrigation at critical growth stages, N application @ 150 kg ha^{-1} and crop residue mulching @ 10 t ha^{-1} resulted in better soil physical quality and maize yield in sandy loam soil of Delhi region.

Key words: Maize, crop residue mulch, least limiting water range, *S* index, mean weight diameter, whole soil stability index

Maintaining soil health is indispensable for sustaining the agricultural productivity at higher level. Indiscriminate use of inputs and unscientific cultivation practices has led to deterioration of soil health. It is estimated that out of the 328 million hectare (Mha) of the total geographical area in India, 120.72 Mha are degraded (Maji *et al*. 2010), producing less than 20% of its potential capacity and out of this, 89.52 Mha suffers from one or the other form of physical constraints leading to deterioration of soil physical health. Mechanization of farm operations, frequent tillage in intensive cropping systems and decline in soil organic matter due to low use/ non use of organic inputs *etc*. are adding new areas with new soil health related problems to the existing area. Soil health/quality includes three groups of mutually interactive attributes *i.e.* soil physical, chemical and biological quality. Soil physical quality/ health is the ability of a given soil to meet plant and ecosystem requirements for water, aeration and strength over time, and also to resist and recover from processes that might diminish that ability (McKenzie 2011). Lal and Stewart (1995) reported that returning crop residues to the soil improved soil quality and

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productivity through favorable effects on soil properties. Soil physical quality can be assessed using some key indices like least limiting water range (LLWR), *S* index, mean weight diameter (MWD), water stable aggregates (%WSA) and whole soil stability index (WSSI). The range in soil water content in which limitations for plant growth associated with matric pressure, aeration and mechanical resistance are minimal was defined as the LLWR (Letey *et al.* 1985; da Silva *et al.* 1994). The concept of a single parameter that describes a range in water contents and incorporates limitations of water content on plant growth related to aeration, soil strength and available water was introduced by Letey (1985). The structural quality of soil could be considered as "very good" for LLWR> 0.20 $m^3 m^{-3}$, "good" for LLWR in between 0.15-0.20 $m^3 m^{-3}$, "moderate" for LLWR in between 0.10-0.15 $m^3 m^{-3}$ and "poor" for LLWR< 0.1 $m^3 m^{-3}$ (da Silva and Kay 1997). Moreover, few studies in the past compared the magnitude of LLWR under different tillage and residue management treatments to predict their impact on surface soil physical conditions under contrast growing seasons (Carter 1988; da Silva and Kay 1997; Betz *et al.* 1998; Lapen *et al.* 2004). Aggarwal *et al.* (2013) reported that bed-planting system was superior to conventional planting as it had wider LLWR indicating better water availability and improved soil structural conditions, which led to enhanced root growth and higher maize yield. They concluded that LLWR could be used as a tool for assessing the suitability of a given soil management practice in improving soil productivity. Similarly, Mishra *et al.* (2015) reported that crop residues resulted in significantly higher LLWR at 0-15 cm in zero tillage (ZT), permanent broad-beds (PBB) and permanent narrow-beds (PNB) systems.

Dexter (2004a,b,c) proposed a single value soil physical quality index, which is likely to be unique for a particular soil type or sensitive to different agri-management practices. This soil physical quality index, *S*, is defined as the slope of the soil water retention curve at its inflection point (Dexter 2004a). The essential premise of *S* theory is that soil physical or structural quality is determined primarily by management-induced "structure" pores, rather than texture-induced "matrix" pores. The structure pores comprise three-dimensional networks of micro-cracks, fractures and inter-aggregate spaces (*i.e.* secondary structure) created by tillage, freeze-thaw activity, addition of amendments, drainage, crop rotations, root development, *etc*. For the most part, structure pores determine the shape of the soil water release curve at tension heads between saturation (h=0) and the inflection point (h=hi). On the other hand, matrix pores, include the spaces within aggregate and between the individual sand, silt, clay and organic matter particles (*i.e.* primary structure), and they largely control soil water release at tension heads greater than the inflection point tension (h>hi). For both temperate and tropical soils, an $S \geq 0.050$ indicates "very good" soil physical or structural quality, while $0.035 \leq S \leq 0.050$ is "good physical quality", $0.020 \leq S \leq 0.035$ is "poor physical quality", and $S < 0.020$ is "very poor" or "degraded" physical quality (Dexter 2004c; Tormena *et al.* 2008). The theoretical limits of S are $0 \leq S < \infty$, however, agricultural soils tend to fall within the range $0.007 \leq S \leq 0.14$ (Dexter and Czyz 2007). In some preliminary studies, this index was found to decrease with increasing bulk density (Cavalieri *et al.* 2009) and is consistent with observations on soil compaction, effects of soil organic matter and root growth but appears to be independent of soil texture. Larger values of *S* are indicative of less compaction and greater organic matter in soils, which promotes better root growth (Dexter 2004a). This is a new concept and need to be evaluated in diverse soils. Moreover, the soil physical environment is greatly modified by different management practices like inorganic and organic inputs, tillage practices as well as soil amendments, which need to be evaluated in terms of *S* index. Sinha *et al.* (2014) reported that there was high and significant correlation between *S* index and soil physical parameter and crop yield, which showed that *S* index can be used effectively for quantifying soil physical quality under diverse environments *vis-a`-vis* crop yield. Soil aggregation is considered as the most important indicator for evaluating soil structure. Aggregation is important in: (i) facilitating water infiltration; (ii) providing adequate habitat space for soil organisms; (iii) adequate oxygen supply to roots and soil organisms; and (iv) preventing soil erosion (Franzluebbers 2002). Thus, MWD, WSA and WSSI are three important indices for assessing soil aggregate stability.

In this background, we hypothesized that crop residue mulch and nitrogen (N) application/ management will improve soil physical health indices. The present investigation was conducted with the objective to study the impact of crop residue mulch, irrigation and N management practices in *kharif* maize on soil physical quality indices like MWD, WSA, WSSI, *S* index and LLWR and their impact on growth and yield of maize crop on a sandy loam soil.

Table 1. Initial properties of the soil of the experimental site

Depth (cm)	Bulk density ($Mg\ m^{-3}$)	pH	EC ($ds\ m^{-1}$)	Saturated hydraulic conductivity ($cm\ h^{-1}$)	SOC ($g\ kg^{-1}$)	Particle size distribution			Soil texture	Soil moisture constants ($cm^3\ cm^{-3}$)	
						Sand	Silt (%)	Clay		0.033 MPa	1.5 MPa
0-15	1.58	7.1	0.46	1.01	4.2	64.00	16.80	19.20	Sl	0.254	0.101
15-30	1.61	7.2	0.24	0.82	2.2	64.40	10.72	24.88	SCl	0.269	0.112
30-60	1.64	7.5	0.25	0.71	1.6	63.84	10.00	26.16	SCl	0.283	0.129
60-90	1.71	7.5	0.25	0.49	1.2	59.84	10.00	30.16	SCl	0.277	0.110
90-120	1.72	7.7	0.30	0.39	1.1	53.68	13.44	32.88	SCl	0.247	0.097

Materials and Methods

Soil and weather condition

The field experiment was conducted during wet season (*kharif* season) of 2012 and 2013 on a Typic Haplustept at the Research Farm of Indian Agricultural Research Institute (IARI), New Delhi with maize (*Zea mays* L.) as a test crop. The experimental site (28°N, 77°E, and 228 m above mean sea level) was located in the Upper-Gangetic Plain (UGP) of India and represented an irrigated, mechanized and input-intensive cropping area. The climate of New Delhi is sub-tropical semi-arid, with dry hot summers (March to June) and brief severe winters (December to February). The average monthly minimum and maximum temperature in January (the coldest month) ranged between 5.9 and 19.9 °C, respectively. The corresponding temperature in May (the hottest month) ranged between 24.4 and 38.6 °C, respectively. The average annual rainfall is 651 mm, and nearly three-fourth of this is received through south-west monsoon during July to September. The soil of the experimental site was sandy loam (Typic Haplustept) of Gangetic alluvial origin, very deep (>2 m), flat and well drained. Detailed soil characteristics were determined at the initiation of the experiment and the data are presented in table 1. It was observed that the soil was mildly alkaline (pH=7.1), non-saline (EC=0.36 dS m^{-1}), low in soil organic C (SOC=4.2 g kg^{-1}, Walkley and Black C) and total N (0.032%) and medium in available P (7.1 kg ha^{-1}) and K (281.0 kg ha^{-1}) content. The soil (0–15 cm) has bulk density (BD) 1.58 Mg m^{-3}; hydraulic conductivity (saturated) 1.01 cm h^{-1}, saturated water content (0.41 $m^3\ m^{-3}$), sand, silt and clay content of 64.0, 16.8 and 19.2%, respectively. Soil water content at 0.033 MPa and 1.5 MPa were 0.25 and 0.101 $m^3\ m^{-3}$, respectively.

Treatment details

The treatments comprising of two levels of irrigation as main plot factor (rainfed and 4 irrigations at critical growth stages *i.e.* seedling, eight leaf stage, tasseling and grain filling stages in the absence of rainfall in these stages), two levels of mulching as sub-plot factor (with and without wheat residue mulching @ 10 t ha^{-1}) and three levels of N as sub-sub-plot factor (0, 75 and 150 kg N ha^{-1}) were laid out in a split-split plot design with three replications. The sub-sub-plot size was 4.5 m × 5 m. Maize (cv. HQPM-1) was sown every year during third week of July at 45 cm × 20 cm spacing and harvested manually during last week of October. Nitrogen was supplied as urea in four splits *i.e.* 20% at sowing, 20% at four leaf stage, 30% at eight leaf stage and rest 30% at tasseling stage. All the plots received a uniform dose of 75 kg P_2O_5 ha^{-1} as single superphosphate and 75 kg K_2O ha^{-1} as muriate of potash applied at sowing. The field was kept weed free by employing manual weeding 3-4 times during crop growth stages. Four irrigations were supposed to be applied in the irrigated treatment at critical growth stages of maize *viz*., seedling, eight leaf stage, tasseling and grain filling stages as per the treatment envisaged in the absence of rainfall during these stages. However, rainfall occurred at two critical growth stages *i.e.*, eight leaf stage and tasseling stage in both the years. So, only 2 irrigations instead of 4 irrigations were applied for both the years of study.

Computation of S index

Water retention by soil at different suctions was determined with a pressure plate apparatus. Volumetric water content was measured at 33, 50, 80, 100, 300, 500, 800 and 1500 kPa soil water suctions to obtain water retention curves. The values of the water content corresponding to each level of suction were then fitted to the Van Genuchten equation:

$$\theta = (\theta_{sat} - \theta_{res}) - [1 + \alpha h^n]^m + \theta_{res} \quad \ldots(1)$$

where, θ is the water content at the suction h ($m^3\ m^{-3}$); θ_{sat} is the water content at saturation ($m^3\ m^{-3}$); θ_{res} residual water content ($m^3\ m^{-3}$); α is the adjustable scaling factor (kPa); h is the water suction (kPa); m and n are adjustable shape factors,

$$m = 1 - 1/n \quad \ldots(2)$$

The value of van Genuchten water retention parameter was obtained using the computer program Rosetta, and then these values were used in the following equation to calculate *S* value

$$S = -n(\theta_{sat} - \theta_{res})\left[\frac{2n-1}{n-1}\right]^{\frac{1}{n}-2} \quad \ldots(3)$$

where, the terms have the same meaning as in eq (1).

Computation of least limiting water range (LLWR) and penetration resistance (PR)

The concept of LLWR characterizes a single range of soil water content beyond which the available water, soil aeration and mechanical resistance impose significant limitations to plant growth. This concept was first developed by da Silva *et al*. (1994).

Since LLWR integrates all these three directly associated factors with plant growth into a single variable, it can be regarded as a useful single value soil physical index required to characterize soil physical environment and more specifically soil structural quality.

Upper limit of LLWR is either soil water content at 10% aeration porosity (θ_{ap}) or soil water content at field capacity (θ_{fc}), whichever is lower, and lower limit is either soil water content corresponding to 2 MPa soil penetration resistance (θ_{2MPa}) or soil water content at wilting point (θ_{pwp}), whichever is higher. Higher the value of LLWR, better would be the soil physical environment for plant growth. Soil BD was determined by core method (Blake and Hartge 1986) at flowering, grain filling stage and harvest of maize crop. Rings with undisturbed soil were used for determination of soil water contents (θ) at field capacity (θ_{fc}) and permanent wilting point (θ_{pwp}) by pressure plate apparatus. Soil water content at saturation (θ_{sat}) was determined gravimetrically. Soil water content at 10% aeration porosity (θ_{ap}) (da Silva *et al*. 1994) was determined by using the following formula:

$$\theta_{ap} = \theta_{sat} - 0.1 \quad \ldots(4)$$

Soil penetration resistance (PR) was measured by Rimik cone penetrometer (model no. CP20, Australia). Soil penetration resistance was measured at 2-3 days interval during drying cycle after each irrigation/rainfall. Soil moisture content (θ of 0-15 and 15-30 cm soil layer) was determined by gravimetric method along with soil penetration measurement. In order to calculate soil water content at 2 MPa soil penetration resistance (θ_{2MPa}), a regression model, which related PR to BD and θw developed by Aggarwal *et al*. (2013) for the same field was used.

$$\text{PR (kPa)} = 903.33 - 182.24\,\theta + 1845.55\,\text{BD} \quad \ldots(5)$$

Calculation of LLWR (% $m^3\ m^{-3}$) and available water retention capacity of soil (AWRC) (% $m^3\ m^{-3}$):

Upper limit of LLWR = θ_{fc} or $\theta_{ap,}$ whichever is lower;

Lower limit of LLWR = θ_{pwp} or θ_{2MPa}, whichever is higher;

Magnitude of LLWR = (Upper limit of LLWR) – (Lower limit of LLWR) …(6)

Magnitude of AWRC = $\theta_{fc} - \theta_{pwp}$ …(7)

Computation of mean weight diameter (MWD) and geometric mean diameter (GMD)

The soil aggregate separation was done using a wet sieve shaker (Yodder apparatus). The MWD and GMD were calculated as indices of aggregation (van Bavel 1949; Kemper and Roseneau 1986) using following formula:

$$\text{MWD} = \Sigma x_i w_i \quad \ldots(8)$$

where, w_i is the proportion of each aggregate class in relation to whole soil, and x_i is the mean diameter of the class (mm).

$$\text{GMD} = \exp[\Sigma(w_i \log x_i)/(\Sigma w_i)] \quad \ldots(9)$$

where, w_i is the weight of aggregates (g) in a size class with an average diameter x_i.

Computation of water stable aggregates (% WSA)

The WSA were computed by adding the aggregates of different size fractions (0.25-8 mm), and expressing them as percentage of the total weight of soil taken for analysis.

Water stable aggregation for each size class was determined as,

$$\text{WSA}_i = [(\text{Wa} - \text{Wc})/\text{Wo}] \times 100 \quad \ldots(10)$$

where, Wa = weight of material on the sieve after wet sieving of size i; Wc = weight of coarse material in size i; Wo = weight of aggregates placed on the sieve prior to wet sieving of size i.

The coarse material (Wc) was determined by dispersing the aggregates of each size group with a dispersing agent 0.5% sodium hexametaphosphate and sieving through the same sieve size.

Table 2. Bulk density and hydraulic conductivity of soil after maize harvest as influenced by irrigation, mulch and nitrogen management

Treatments	BD (Mg m^{-3})			Hydraulic conductivity (cm h^{-1})		
	0-5 cm	5-15 cm	15-30 cm	0-5 cm	5-15 cm	15-30 cm
Irrigation effect						
Rainfed	1.46b*	1.71a	1.73a	0.65a	0.23a	0.21a
Irrigated	1.54a	1.72a	1.68a	0.63a	0.25a	0.32a
Mulch effect						
Without mulch	1.51a	1.73a	1.72a	0.62b	0.21b	0.27a
Wheat residue mulch @ 10 t ha^{-1}	1.49b	1.70b	1.69b	0.66a	0.28a	0.26a
Nitrogen effect						
Control	1.53a	1.72a	1.72a	0.37c	0.16c	0.19c
75 kg N ha^{-1}	1.46b	1.72a	1.70a	0.62b	0.31a	0.35a
150 kg N ha^{-1}	1.51a	1.70a	1.69a	0.94a	0.26b	0.27b

**Values in a column followed by same letters are not significantly different at p<0.05 as per Duncan's Multiple Range Test (DMRT)*

Computation of whole soil stability index (WSSI)

The WSSI (Nicholas and Toro 2011) was determined using the equation given below:

$$WSSI = \lfloor \sum_i^n [(I) \times (P_{ai}) \times ((WSA_i)/100)] \rfloor / n \quad \ldots(11)$$

where, WSSI = whole soil stability index; n = the number of the aggregate size classes; i = n and decreases by an increment of 1 from the largest to the smallest aggregate sizes class; P_{ai} = proportion of aggregate weight for each size class i.

Results and Discussion

Bulk Density and Soil Hydraulic Conductivity

Application of crop residue mulch (CRM) significantly reduced the BD by 1.3, 1.8 and 1.8 per cent at 0-5, 5-15 and 15-30 cm soil depth, respectively over no-mulch (Table 2). The decrease in BD under crop residue mulch than the no-mulch treatment was mainly attributed to improvement of soil structure as evidenced by increase in MWD, %WSA and porosity because of protection of soil from disruption by rain water impact under crop residue mulch. This result is in agreement with the findings of Acharya *et al.* (2005), Hati *et al.* (2006), Leroy *et al.* (2008) and Celik *et al.* (2010). Application of irrigation significantly increased BD by 5.5 per cent over rainfed treatment at 0-5 cm soil depth; whereas; the effect of irrigation was not significant on BD at 5-15 and 15-30 cm soil depth. Application of N @ 75 kg ha^{-1} registered significantly lower BD at 0-5 cm soil depth than control.

Application of crop residue mulch significantly increased the SHC at 0-5 and 5-15 cm soil depth by 6.4 and 31.3 per cent, respectively over no-mulch (Table 2). However, the effect of crop residue mulch was not significant on SHC at 15-30 cm soil depth. The increased saturated hydraulic conductivity due to crop residue mulch can be ascribed to decrease in BD, increase in total porosity and better soil aggregation because of higher organic matter addition in this treatment. Application of N @ 75 and 150 kg ha^{-1} significantly increased the SHC by 67.6 and 150, 93.8 and 62.5 and 84.2 and 42.1 per cent compared to control at 0-5, 5-15 and 15-30 cm soil depth, respectively. This is mainly attributed to increased root biomass and soil organic carbon and decreased soil BD under this treatment. These results are in agreement with the findings of Lal (1987) and Bandyopadhyay *et al.* (2010).

Soil Moisture Constants

Soil moisture content at field capacity (FC), permanent wilting point (PWP), available water capacity (AWC) and maximum water holding capacity (MWHC) as influenced by irrigation, crop residue mulching and N management have been presented in table 3. Regardless of soil depth, irrigation, crop residue mulch and N application were not significant on FC and PWP. The effects of irrigation, crop residue mulch and N were also not significant on AWC and MWHC, regardless of soil depth.

Soil Penetration Resistance (PR)

It was observed that application of crop residue mulch significantly reduced the soil penetration resistance (PR) by 5 per cent compared to the no-mulch treatment up to 14 cm soil depth (Fig. 1). However, below this depth the effect of crop residue mulch was not consistent on soil PR. Probably

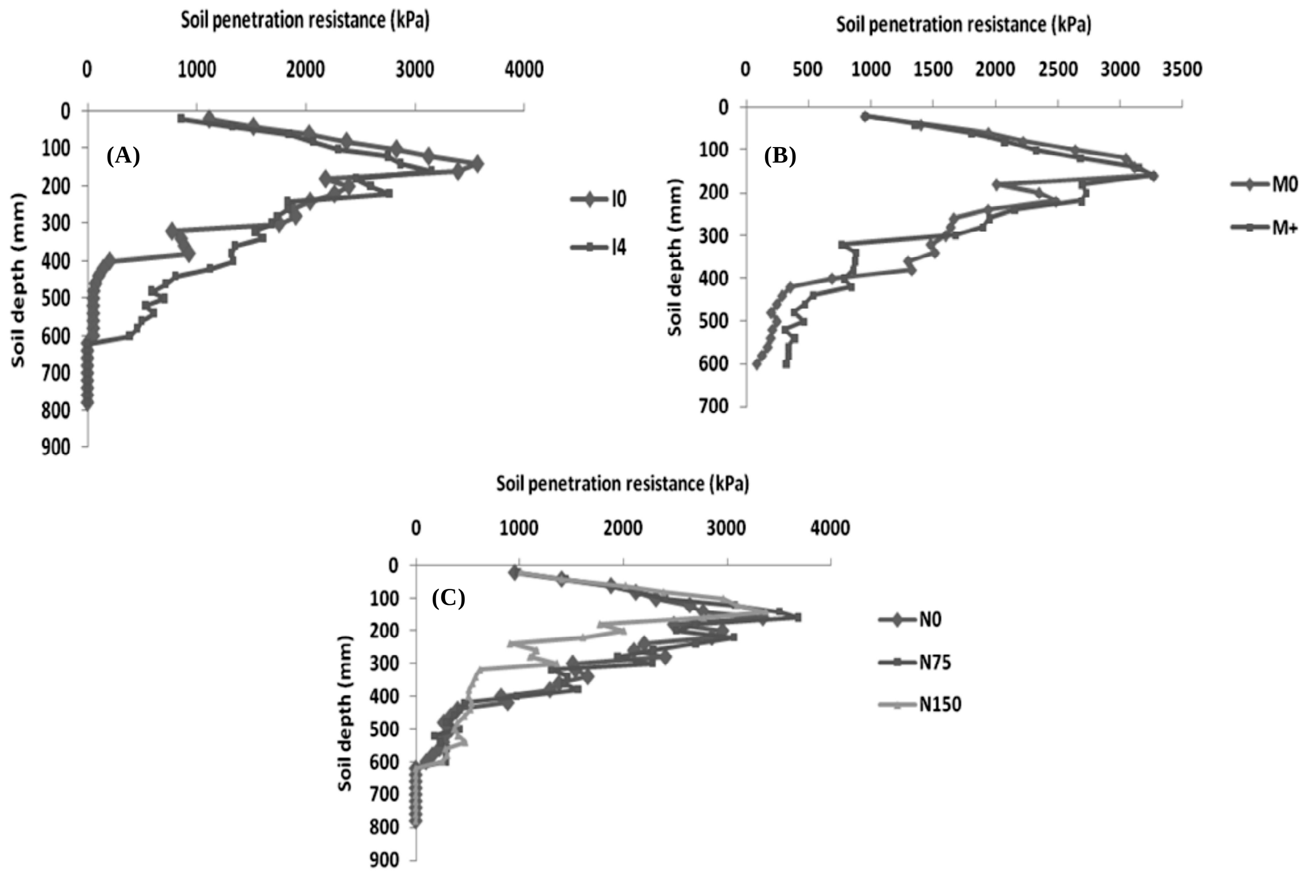

Fig. 1. Soil penetration resistance at 67 days after sowing of maize 2013 as influenced by, (A) irrigation, (B) wheat residue mulch and (C) nitrogen application

Table 3. Volumetric moisture content at field capacity (FC), permanent wilting point (PWP), available water capacity (AWC) and maximum water holding capacity (MWHC) of soil after harvest of maize as influenced by irrigation, mulch and nitrogen management

Treatments	FC		PWP		AWC		MWHC	
	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm	0-15 cm	15-30 cm
Irrigation effect								
Rainfed	0.18a*	0.18a	0.09a	0.09a	0.10a	0.10a	0.38a	0.37a
Irrigated	0.19a	0.19a	0.10a	0.10a	0.09a	0.08a	0.35a	0.34a
Mulch effect								
Without mulch	0.18a	0.18a	0.09a	0.09a	0.10a	0.09a	0.37a	0.36a
Wheat residue mulch @ 10 t ha^{-1}	0.19a	0.19a	0.10a	0.10a	0.10a	0.09a	0.37a	0.35a
Nitrogen effect								
Control	0.19a	0.19a	0.10a	0.10a	0.10a	0.09a	0.37a	0.34a
75 kg N ha^{-1}	0.18a	0.18a	0.09a	0.10a	0.09a	0.08a	0.37a	0.37a
150 kg N ha^{-1}	0.19a	0.19a	0.09a	0.09a	0.09a	0.10a	0.36a	0.35a

* *Values in a column followed by same letters are not significantly different at $p<0.05$ as per DMRT*

decrease of BD and increase in soil moisture storage under crop residue mulch at this soil depth resulted in reduced PR. Application of irrigation significantly reduced the PR by 15.4 and 7.2 per cent at 0-15 and 15-30 cm soil depth, respectively over rainfed treatment. However, we did not observe the significant effect of N on soil PR.

Table 4. Mean weight diameter (MWD), geometric mean weight diameter (GMD), water stable aggregates (WSA) and whole soil stability index (WSSI) as influenced by irrigation, mulch and nitrogen management

Treatments	MWD (mm)	GMD (mm)	WSA (%)	WSSI
Irrigation effect				
Rainfed	0.70b	1.45a	39.78a	0.026a
Irrigated	0.85a	1.45a	42.37a	0.025a
Mulch effect				
Without mulch	0.75b	1.44a	38.43b	0.025a
Wheat residue mulch @ 10 t ha^{-1}	0.80a	1.45a	43.73a	0.026a
Nitrogen effect				
Control	0.70c	1.45a	39.22b	0.022c
75 kg N ha^{-1}	0.79b	1.44a	41.23a	0.025b
150 kg N ha^{-1}	0.84a	1.45a	42.78a	0.029a

**Values in a column followed by same letters are not significantly different at $p<0.05$ as per DMRT*

Mean Weight Diameter, Geometric Mean Diameter, percent Water Stable Aggregates and Whole soil Stability Index

Averaged over crop residue mulch and N levels, application of irrigation registered significantly higher MWD by 21.4 per cent over the rainfed treatment (Table 4). Application of mulch significantly increased the MWD by 6.7 per cent than no-mulch treatment. Application of 75 and 150 kg N ha^{-1} significantly increased MWD by 12.9 and 20 per cent, respectively over control after harvesting of maize. Application of crop residue mulch registered significantly higher WSA by 7.8 per cent over the no-mulch treatment. The effect of irrigation was not significant on %WSA. Application of N @ 75 and 150 kg ha^{-1} significantly increased %WSA by 5.1 and 9.0 per cent, respectively over control after maize harvest. The increase in MWD and %WSA due to irrigation, mulch and N application are mainly attributed to increase in soil organic matter because of organic inputs from crop residues as well as root biomass and reduced disruptions of soil aggregates by rain drop impact. Our results are in agreement with the findings of Emerson (1977), Tisdall and Oades (1980) and Majumdar and Kuzyakov (2010).

The GMD ranged from 1.38 mm to 1.54 mm with a mean value of 1.45 mm. Effect of irrigation, crop residue mulch and N was not statistically significant on GMD. The WSSI at 0-5 cm soil depth ranged from 0.017 to 0.037 with a mean value of 0.026 after maize harvest. The effect of irrigation was not significant on WSSI; whereas application of crop residue mulch improved WSSI by 6.5 per cent over the no-mulch treatment. Application of N @ 75 kg ha^{-1} significantly increased WSSI by 12.4 per cent over control. Similarly, application of 150 kg N ha^{-1} significantly increased WSSI by 14.4 per cent compared to 75 kg N ha^{-1}. The increase in WSSI due to crop residue mulch and N application is mainly attributed to improvement of soil structure due to carbon input from root biomass addition. Similarly, Nicholas and Toro (2011) reported significantly higher WSSI under moderately grazed pasture than that of conventional till fallow lands.

Soil Moisture Characteristics and S-index

Soil moisture characteristics for 0-15 cm soil depth after maize harvest has been depicted in fig. 2 and 3 for no-mulch treatment and crop residue mulch treatment, respectively. These soil moisture retention data were fitted to power functions and these equations have been presented in table 5. It was observed that the change in 'Ψ' per unit change in 'θ' was faster under mulch treatment. Similar results have been reported by Pradhan *et al.* (2013). These soil moisture characteristics data were used to find out van-Genuchten parameters using Rosetta model (Soil Science Laboratory, USA) as shown in table 6. The residual soil moisture (θ_r) ranged from 0.029 to 0.038 with a mean value of 0.032 cm^3 cm^{-3}. The value of saturated moisture content (θ_s) ranged from 0.304 to 0.397 cm^3 cm^{-3} with a mean value of 0.352 cm^3 cm^{-3}. These values are in agreement with the observed θ_s. Saturated moisture content (θ_s) under crop residue mulch (0.370 cm^3 cm^{-3}) was relatively higher than that of no mulch treatment (0.335 cm^3 cm^{-3}). The value of scaling factor (α) ranged from 0.008 to 0.037 cm^{-1} with a mean value of 0.018 cm^{-1}. Application of crop residue mulch registered relatively higher value of 'α' (0.032 cm^{-1}) than that of no-mulch treatment (0.014 cm^{-1}). The value of shape factor 'n' ranged from 1.325 to 1.428 with a mean value of 1.361. The

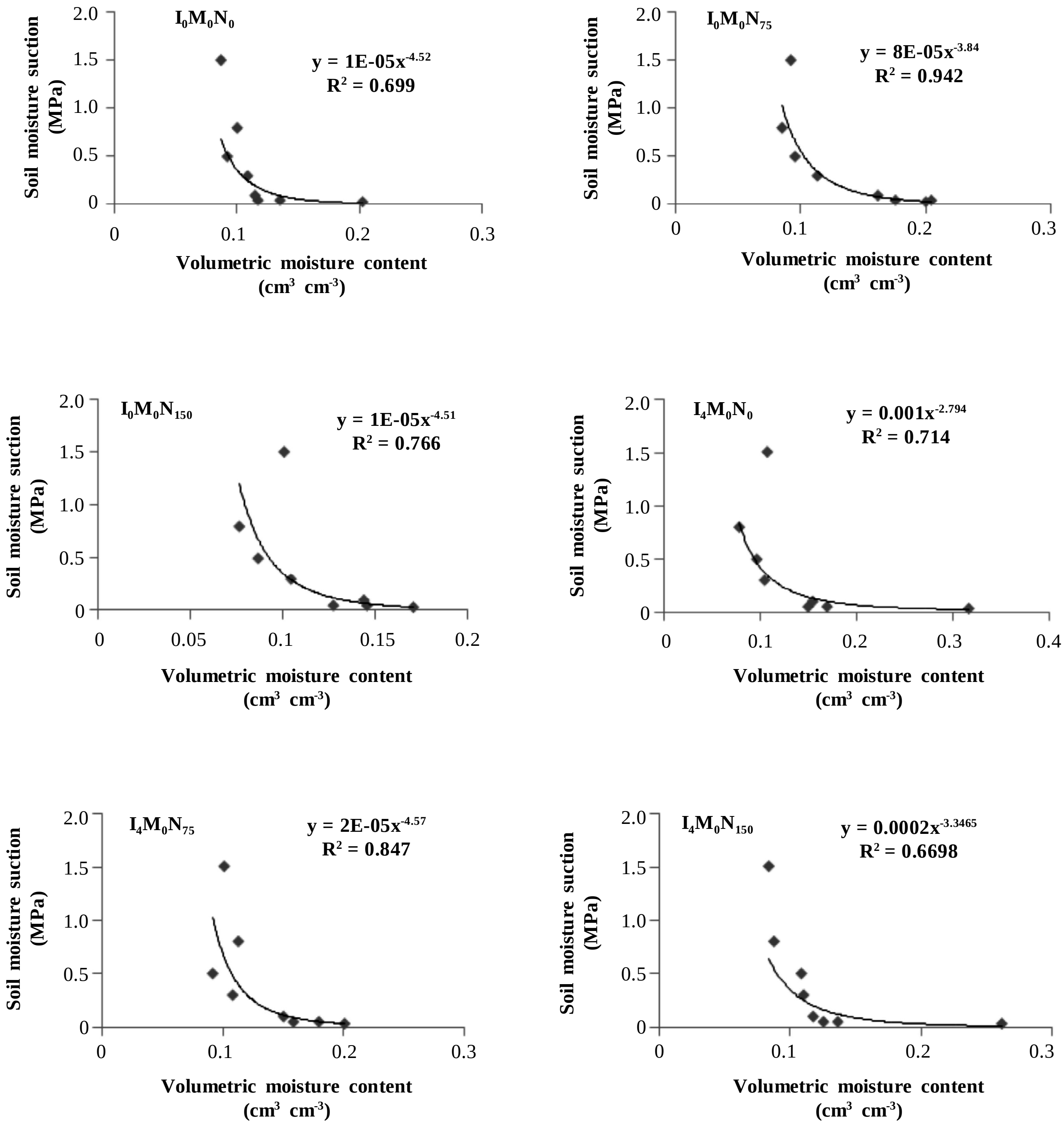

Fig. 2. Soil moisture characteristics curve for 0-15 cm soil depth after maize harvest without mulching

value of 'n' under crop residue mulch (1.358) was relatively lower than no-mulch treatment (1.364). The value of saturated hydraulic conductivity (K_s) as predicted by the model ranged from 4.738 to 80.02 cm d^{-1} with a mean value of 31.32 cm d^{-1} was higher than the observed value under field condition, ranging from 5.8 to 27.02 cm d^{-1} with a mean value of 15.4 cm d^{-1}. The value of 'K_o', *i.e.*, matching point hydraulic conductivity at saturation, ranged from 3.10 to 21.41 with a mean value of 9.10 cm d^{-1}. This value is in agreement with observed value under field condition. The value of 'L' (pore tortuosity parameter) ranged from -1.309 to -0.096 with a mean value of -0.749. Under crop residue mulch treatment, the value of 'L' was -0.902 compared to -0.597 under no-mulch treatment. These parameters were used to compute

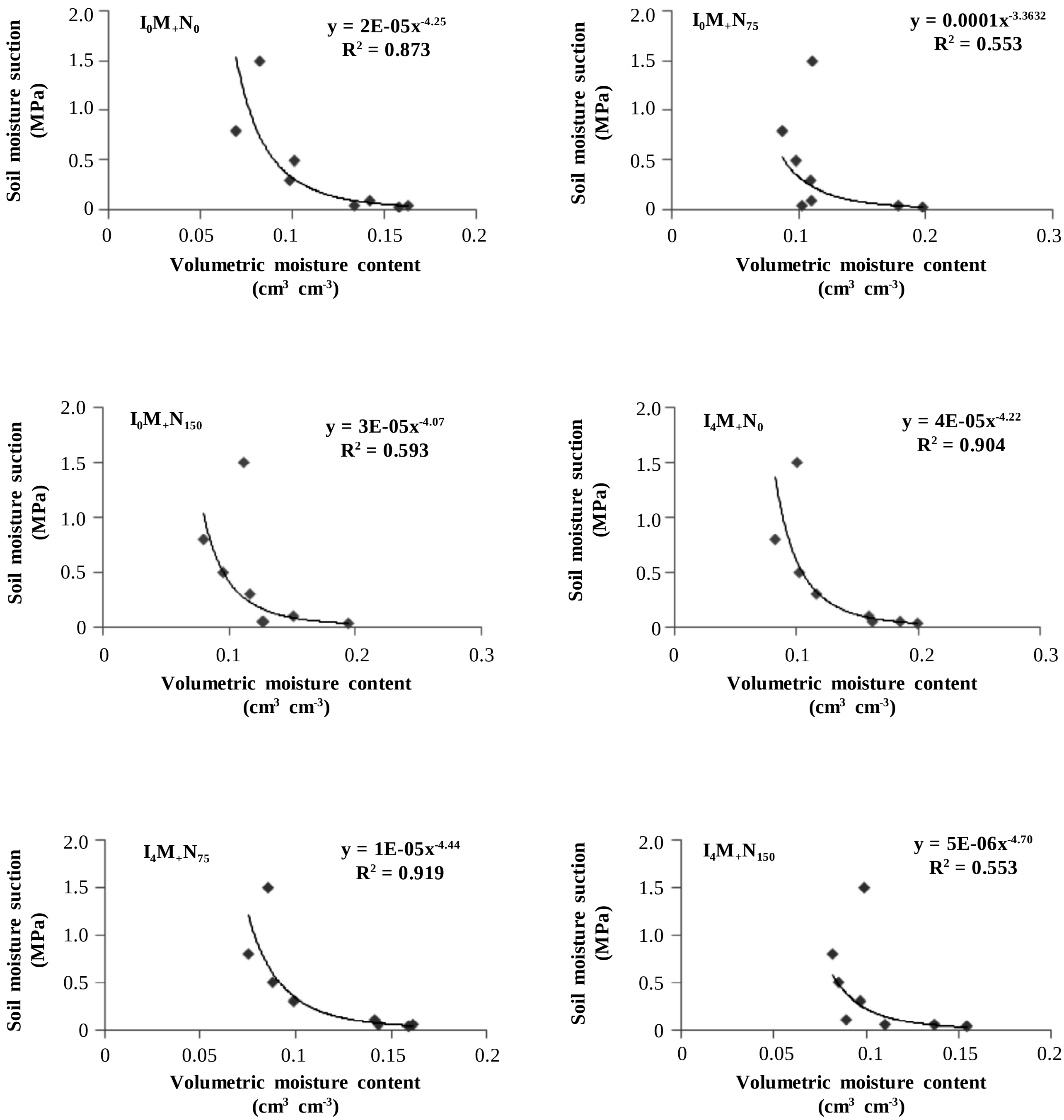

Fig. 3. Soil moisture characteristics curve at 0-15 cm soil depth after maize harvest under wheat residue mulch

the *S* index (Dexter 2004a,b), which is the slope of soil moisture characteristics curve (SMCC) at the inflection point.

The *S* index value ranged from 0.048 to 0.067 with a mean value of 0.060, which was higher than the critical value of 0.05 (Fig. 4). So in general the physical condition of this soil may be rated as very good as per *S* index (Dexter and Czyz 2007; Tormena *et al.* 2008). Application of irrigation significantly increased the *S* index by 3.5 per cent, whereas, application of crop residue mulch significantly increased *S* index by 9.9 per cent over no mulch treatment. Application of N @ 150 kg ha^{-1} significantly increased *S* index by 4.3 per cent over control; whereas, there was no significant difference in *S* index due to 75 kg N ha^{-1} and control. The

Table 5. Soil moisture characteristics equations showing relationship between matric suction (Ψ) (MPa) and volumetric moisture content (θ) ($cm^3\ cm^{-3}$)

Treatment	Soil moisture characteristic equation	R^2
$I_0M_0N_0$	Ψ = 1E-05 $\theta^{-4.52}$	0.699**
$I_0M_0N_{75}$	Ψ = 8E-05 $\theta^{-3.84}$	0.942**
$I_0M_0N_{150}$	Ψ = 1E-05 $\theta^{-4.51}$	0.766**
$I_0M_+N_0$	Ψ = 2E-05 $\theta^{-4.25}$	0.873**
$I_0M_+N_{75}$	Ψ = 1E-04 $\theta^{-3.36}$	0.463*
$I_0M_+N_{150}$	Ψ = 3E-05 $\theta^{-4.07}$	0.593*
$I_4M_0N_0$	Ψ = 1E-03 $\theta^{-2.79}$	0.714**
$I_4M_0N_{75}$	Ψ = 2E-05 $\theta^{-4.57}$	0.847**
$I_4M_0N_{150}$	Ψ = 2E-04 $\theta^{-3.35}$	0.670**
$I_4M_+N_0$	Ψ = 4E-05 $\theta^{-4.22}$	0.904**
$I_4M_+N_{75}$	Ψ = 1E-05 $\theta^{-4.44}$	0.919**
$I_4M_+N_{150}$	Ψ = 5E-06 $\theta^{-4.70}$	0.553*

*Significant at $p< 0.05$; **Significant at $p< 0.01$
I_0 = Rainfed; I_4= four irrigations at critical growth stages: M_0= without mulch; M_+= wheat residue mulch @ 10 t ha^{-1}; N_0= control; N_{75}= 75 kg N ha^{-1}; N_{150}= 150 kg N ha^{-1}

increase in the *S* index under mulched condition may be attributed to decrease in BD and increase in MWD and SOC under this study. Garg *et al.* (2009) reported that *S* index was significantly negatively correlated with BD and significantly positively correlated with SOC and available water capacity (AWC).

Least Limiting Water Range (LLWR)

Soil moisture content at FC, PWP, 10% air filled porosity (AFP) and at 2 MPa soil penetration resistance (PR) were used to compute the LLWR (da Silva and Kay 1997) at flowering (67 DAS), late grain filling stage (95 DAS) and physiological maturity**.** Soil moisture content (SMC) at 10% AFP, FC, PWP and at 2 MPa PR for different soil BD during crop growth has been depicted in fig. 5 and 6 for no-mulch and crop residue mulch treatment, respectively. The SMC at 10% AFP ranged from 0.25 to 0.31$cm^3\ cm^{-3}$ and 0.25 to 0.27 $cm^3 cm^{-3}$ at 0-15 and 15-30 cm soil depth under no-mulch treatment, whereas, under crop residue mulch the corresponding SMC varied from 0.29 to 0.32 and 0.26 to 0.28 $cm^3\ cm^{-3}$ for 0-15 and 15-30 cm soil depth, respectively. The effect of crop residue mulch on SMC at FC and PWP was not statistically significant at 0-15 and 15-30 cm soil depth. The SMC at FC ranged from 0.17 to 0.20 and 0.19 $cm^3\ cm^{-3}$ at 0-15 and 15-30 cm soil depth, respectively under no mulch treatment, whereas the corresponding values under mulch treatment ranged from 0.17 to 0.21 and 0.18 to 0.20 $cm^3\ cm^{-3}$ at 0-15 and 15-30 cm soil depth. The SMC at PWP ranged from 0.08 to 0.09 and 0.08 to 0.10 $cm^3\ cm^{-3}$ at 0-15 and 15-30 cm soil depth under no-mulch treatment; whereas, under crop residue mulch PWP ranged from 0.08 to 0.10 and 0.09 to 0.11 $cm^3\ cm^{-3}$ at 0-15 and 15-30 cm soil depth, respectively. The BD ranged from 1.56 to 1.73 and 1.67 to 1.72 Mg m^{-3} at 0-15 and 15-30 cm soil depth during the days of observation under no-mulch treatment; whereas, under crop residue mulch the BD values ranged from 1.56 to 1.61 and 1.65 to 1.70 Mg m^{-3} at 0-15 and 15-30 cm soil depth, respectively. The BD values were used to compute SMC at 2 MPa soil PR using the relationship

Table 6. vanGenuchten Model parameters for soil moisture characteristics as derived from Rosetta model

Treatment	θ_r	θ_s	α	n	k_s	k_0	L	m
$I_0M_0N_0$	0.0322	0.3334	0.020054	1.33906	21.33045	9.10542	-1.0377	0.2532
$I_0M_0N_{75}$	0.0303	0.3041	0.012703	1.325257	5.803634	5.318633	-0.801	0.2454
$I_0M_0N_{150}$	0.0292	0.3367	0.008484	1.428236	12.62699	3.658474	-0.0962	0.2998
$I_0M_+N_0$	0.0335	0.3944	0.022683	1.352695	58.26396	12.66777	-0.8733	0.2607
$I_0M_+N_{75}$	0.0311	0.3571	0.023458	1.355189	43.01303	11.98119	-1.0086	0.2621
$I_0M_+N_{150}$	0.0299	0.3473	0.017993	1.361445	29.47813	8.767989	-0.7896	0.2655
$I_4M_0N_0$	0.0339	0.3522	0.013593	1.362072	17.23455	5.975854	-0.5784	0.2658
$I_4M_0N_{75}$	0.0300	0.3496	0.018235	1.361758	30.93143	8.949525	-0.7921	0.2657
$I_4M_0N_{150}$	0.0353	0.3317	0.008272	1.365212	4.738054	3.103845	-0.2744	0.2675
$I_4M_+N_0$	0.0329	0.3366	0.012266	1.359878	11.59044	5.195173	-0.5536	0.2646
$I_4M_+N_{75}$	0.0381	0.386	0.037231	1.366155	80.02027	21.40918	-1.3092	0.2680
$I_4M_+N_{150}$	0.0335	0.397	0.023036	1.352384	60.85552	13.03467	-0.8783	0.2606

θ_s = Saturated moisture content; θ_r = residual soil moisture content; α = scaling factor; n = shape factor; K_s = saturated hydraulic conductivity; K_o = matching point hydraulic conductivity at saturation; L = pore tortuosity parameter; m = m = 1-1/n adjustable shape factor
I_0 = Rainfed; I_4= four irrigations at critical growth stages; M_0= without mulch; M_+= wheat residue mulch @ 10 t ha^{-1}; N_0= control; N_{75}= 75 kg N ha^{-1}; N_{150}= 150 kg N ha^{-1}

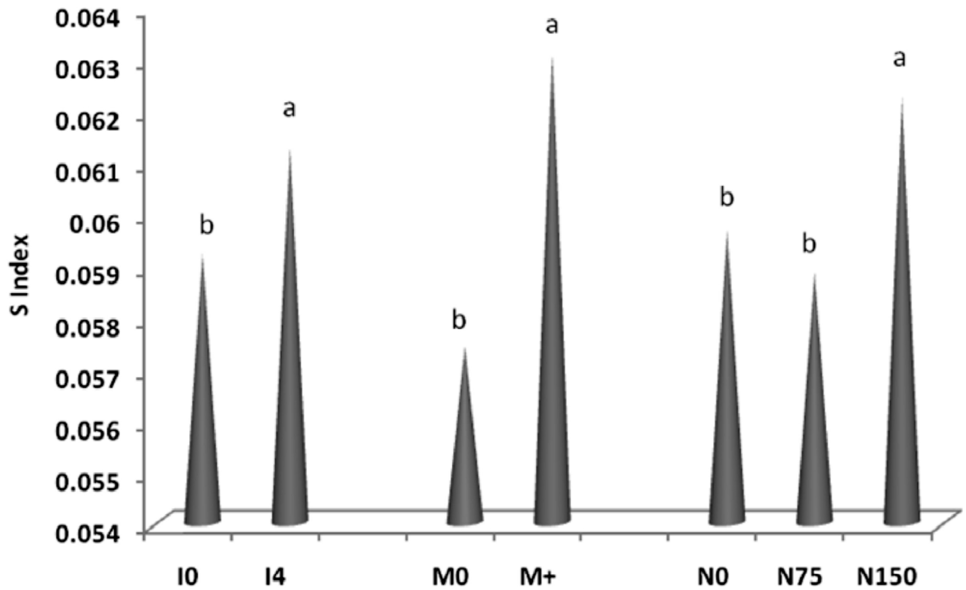

Fig. 4. *S* index at maize harvest as influenced by irrigation, mulch and nitrogen management

developed be Aggarwal *et al.* (2013). The SMC at 2 MPa PR ranged from 0.10 to 0.11 $cm^3\ cm^{-3}$ at 0-15 and 15-30 cm soil depth both under mulch and no-mulch treatment.

The LLWR as influenced by irrigation, crop residue mulch and N management during the growth stages of maize has been depicted in fig. 7. The LLWR values ranged from 0.01 to 0.11 $cm^3\ cm^{-3}$ with a mean value of 0.09 $cm^3\ cm^{-3}$ and from 0.02 to 0.11 $cm^3\ cm^{-3}$ with a mean value of 0.08 $cm^3\ cm^{-3}$ at 0-15 and 15-30 cm soil depth, respectively at 67 DAS. At 95 DAS, the LLWR values ranged from 0.02 to 0.09 $cm^3\ cm^{-3}$ with a mean value of 0.07 $cm^3\ cm^{-3}$ and from 0.06 to 0.10 $cm^3\ cm^{-3}$ with a mean value of 0.08 $cm^3\ cm^{-3}$ at 0-15 and 15-30 cm soil depth, respectively. Based on the LLWR values the structural quality of soil could be rated as poor to moderate (da Silva and Kay 1997). There was significant increase in LLWR at 0-15 cm soil depth due to crop residue mulch and N application at flowering, grain filling and physiological maturity stages. The increase in LLWR with mulch application in the present study may be attributed to improvement of soil structure as evident from higher MWD, %WSA and decrease in BD under mulching than that of no-mulch treatment. Similarly, improvement of MWD and %WSA under N application might have resulted in higher LLWR in this treatment than the control at 0-15 cm soil depth.

Application of irrigation significantly increased the LLWR by 16.8 and 40.6 per cent over the rainfed treatment at 67 DAS and harvest at 0-15cm soil depth. However, at 95 DAS there was significant reduction in the LLWR due to irrigation by 36.4 and 20.5 per cent at 0-15 and 15-30 cm soil depth, respectively. Application of crop residue mulch significantly increased LLWR by 48.3, 11.4 and 31.6 per cent over no-mulch treatment at 0-15 cm soil depth at 67 and 95 DAS and at harvest, respectively. However, the effect of crop residue mulch on LLWR at 15-30 cm soil depth was not significant in these days. At 95 DAS, application of 75 kg N ha^{-1} significantly increased the LLWR by 32.2 and 17.0 per cent at 0-15 and 15-30 cm soil depth, respectively. Application of 150 kg N ha^{-1} significantly increased the LLWR by 23 and 12 per cent over control at 0-15 and 15-30 cm soil depth, respectively. However, there was no significant difference between 75 and 150 kg N ha^{-1} with respect to LLWR on these days, regardless of soil depths. At harvest, application of N registered significantly lower LLWR than the control at 0-15 cm soil depth whereas at 15-30 cm soil depth, the effect of N was not significant on LLWR at 67 DAS and harvest.

Root growth of maize at flowering stage under irrigation, nitrogen and mulch application

It was observed that the root length density of maize at 0-15 cm soil depth increased significantly by 22.4, 14.4 and 42.7 per cent due to irrigation, crop residue mulch and N application, respectively (Table 7). The root mass density of maize at 0-15 cm soil depth increased by 44.4 and 92.9 per cent due to crop

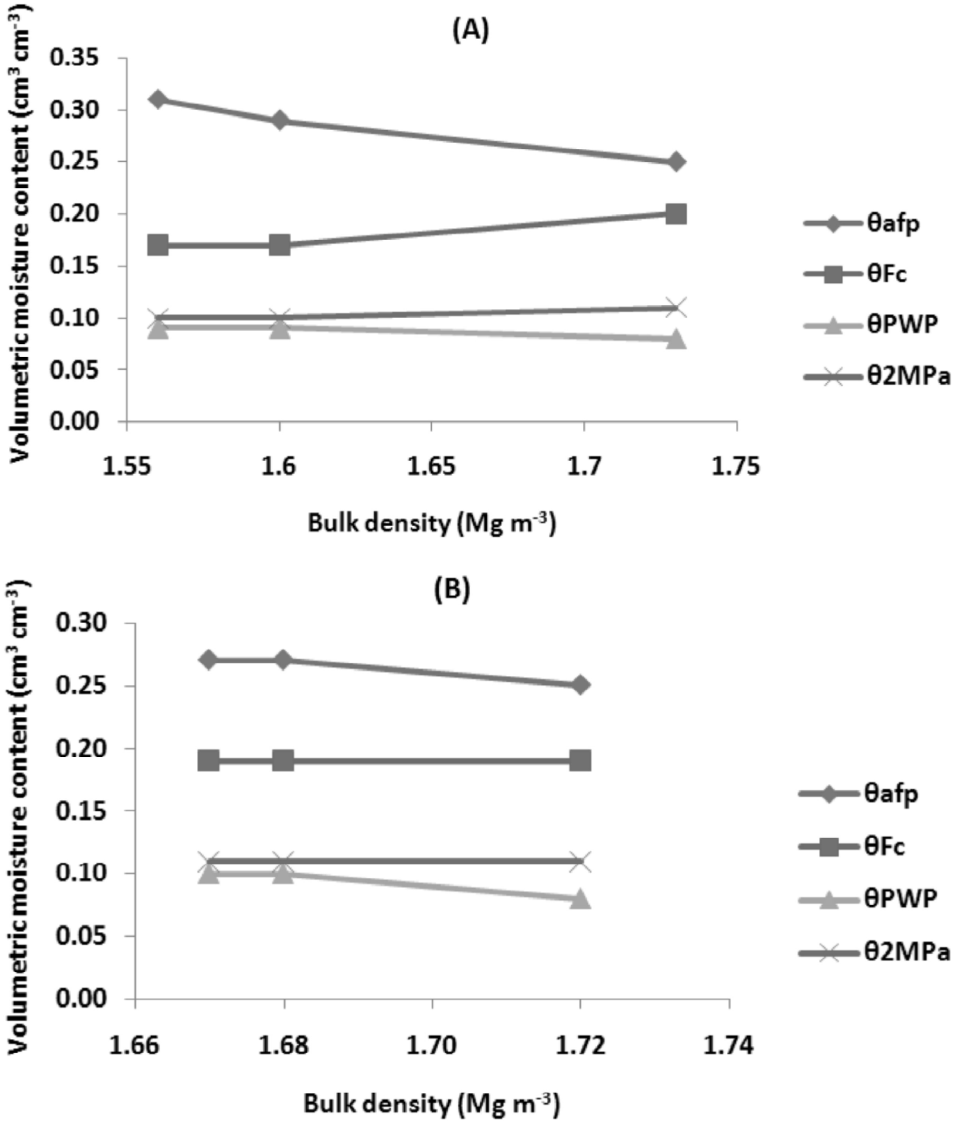

Fig. 5. Soil moisture content at 10% air filled porosity (θ_{afp}), field capacity (θ_{FC}), permanent wilting point (θ_{PWP}) and 2 MPa soil strength (θ_{2MPa}) under different bulk densities at (A) 0-15 cm and (B) 15-30 cm soil depth during maize growth without mulch

residue mulch and N application, respectively. Better availability of soil moisture and better thermal regime under mulched condition might have facilitated better root growth. Chakraborty *et al*. (2010) also reported significantly higher root weight and root length densities under mulched treatment compared to no-mulch treatment in wheat. Similar to our study, Durieux *et al.* (1994) reported that application of N fertilizer stimulated root growth at surface but not at lower depths.

Grain and biomass yield of maize under irrigation, nitrogen and mulch application

The grain and biomass yield of maize pooled over 2012 and 2013, increased by 28.4 and 40.0 per cent, respectively due to crop residue mulching (Table 7). The increased crop productivity due to crop residue mulching has also been reported by several workers (Khurshid *et al*. 2006; Pervaiz *et al*. 2009; Chakraborty *et al*. 2010; Uwah and Iwo 2011). Application of N @ 75 and 150 kg ha^{-1} increased the pooled grain yield of maize by 44.6 and 52.5 per cent and biomass yield of maize by 47.8 and 49.9 per cent, respectively. Our results were congruent with the findings of Pradhan *et al*. (2013), who have reported significantly higher grain and biomass yield of maize due to N application.

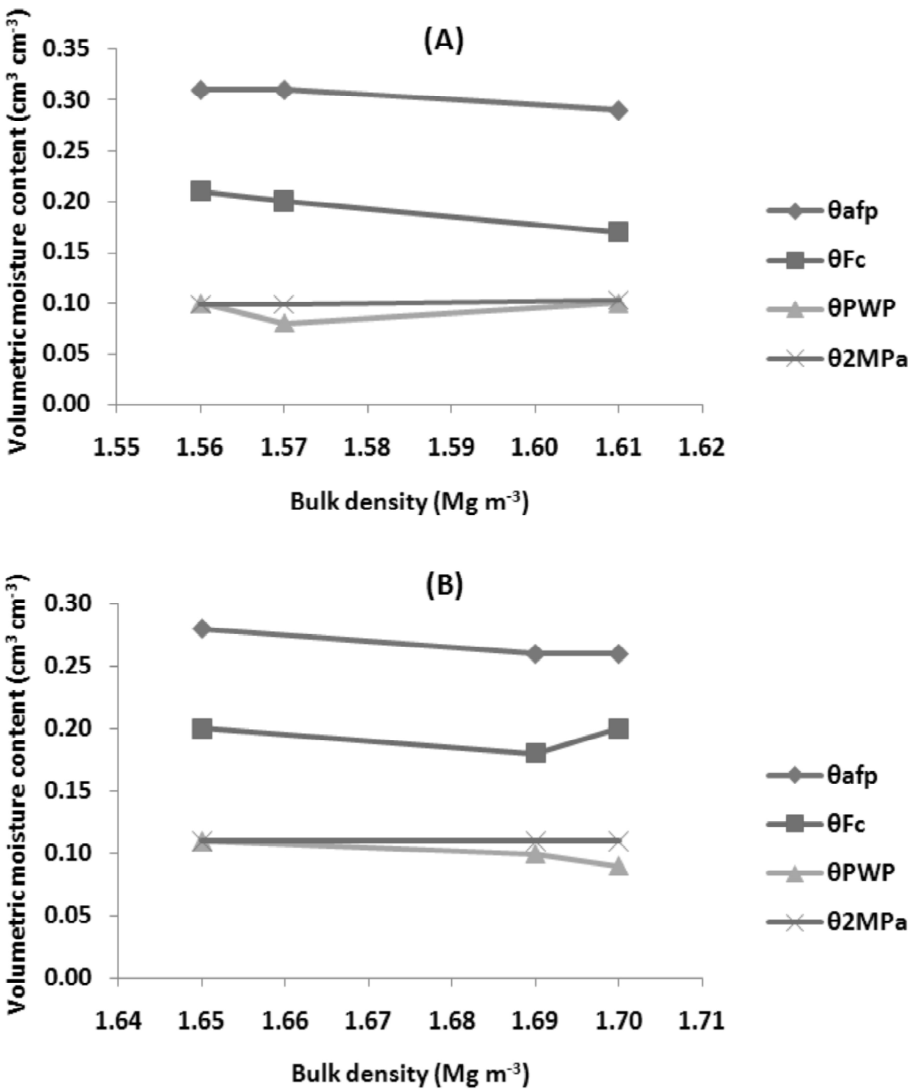

Fig. 6. Soil moisture content at 10% air filled porosity (θ_{afp}), field capacity (θ_{FC}), permanent wilting point (θ_{PWP}) and 2 MPa soil strength (θ_{2MPa}) under different bulk densities at 0-15 cm and 15-30 cm soil depth during maize growth with wheat residue mulch

Correlation between Physical properties of soil, root growth and grain and biomass yield of maize

It was observed that root length density (RLD) (r = 0.50*) and root mass density (RMD) (r = 0.55*) were significantly positively correlated with saturated hydraulic conductivity of soil (Table 8). The grain yield of maize was significantly positively correlated with saturated hydraulic conductivity (r = 0.67**) and root mass density of maize at 0-15 soil depth (r = 0.63**). Similarly the biomass yield of wheat was significantly positively correlated with saturated hydraulic conductivity (r = 0.52*), RLD (r = 0.50*) and RMD (r = 0.68**) of maize. Among the soil physical indices, *S* index was not significantly correlated with root growth, crop yield or any other soil physical properties. However, Sinha *et al.* (2014) reported significantly positive correlation of *S* index with SOC and MWD but it had a significant negative relationship with BD. They also observed significantly positive relationship between *S* index and yield of maize and wheat crop in a Vertisol. The LLWR was significantly positively correlated with MWD (r = 0.50*). Aggarwal *et al.* (2013) observed significant negative correlation between LLWR and BD of soil. In contrast, Safadoust *et al*. (2014) reported that LLWR was significantly positively related to BD, clay and organic carbon content. Available water capacity of soil was significantly positively correlated with

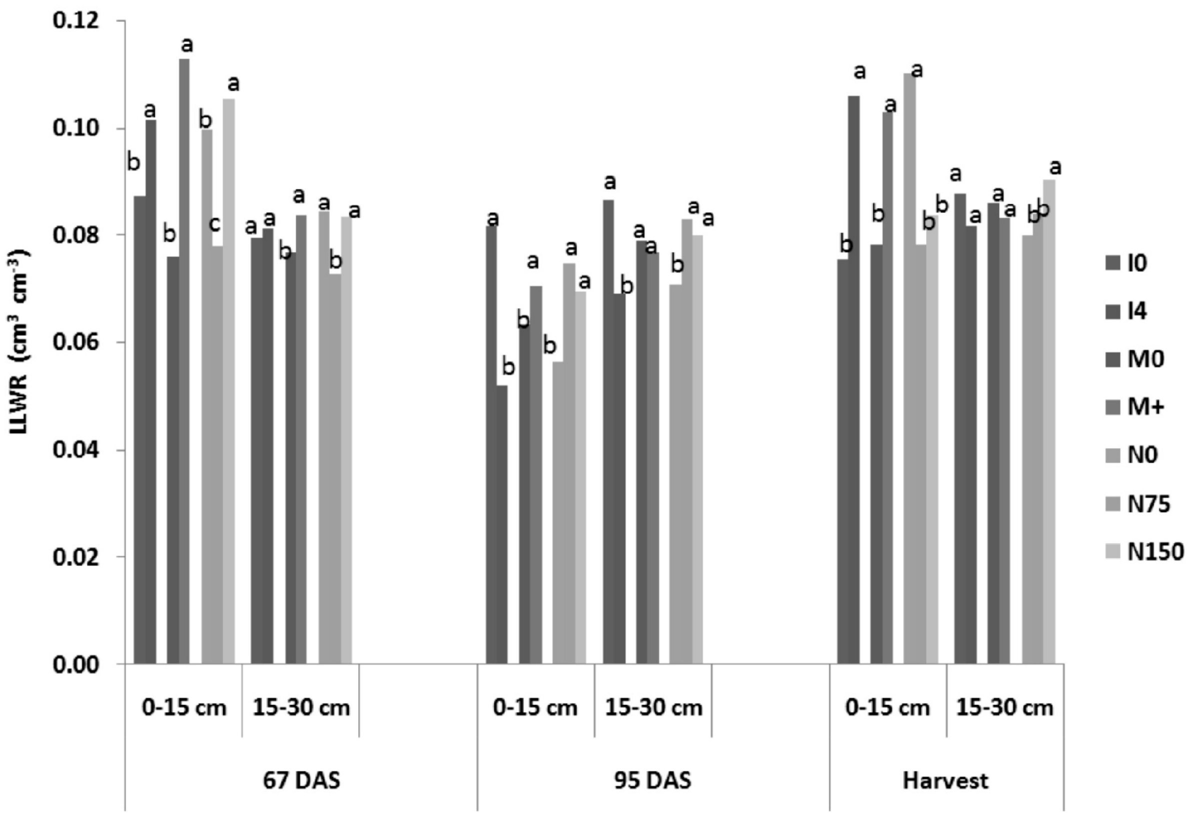

Fig. 7. Least limiting water range (LLWR) during maize growth as influenced by irrigation, mulch and nitrogen management

Table 7. Root growth and yield of maize as influenced by irrigation, crop residue mulch and nitrogen fertilization (Pooled over 2012 and 2013)

Treatments	Root length density at 0-15 cm (cm cm^{-3})	Root mass density at 0-15 cm (g cm^{-3})	Grain yield (kg ha^{-1})	Biomass (kg ha^{-1})
Irrigation effect				
Rainfed	2.619b*	0.011a	4352a	16204a
Irrigated	3.205a	0.011a	4421a	16644a
Mulch effect				
Without mulch	2.717b	0.009b	3841b	13687b
Wheat residue mulch @ 10 t ha^{-1}	3.107a	0.013a	4933a	19161a
Nitrogen effect				
Control	2.267c	0.007b	3314c	12388c
75 kg N ha^{-1}	2.757b	0.013a	4793b	18312b
150 kg N ha^{-1}	3.714a	0.014a	5054a	18573a

**Values in a column followed by same letters are not significantly different at p<0.05 as per DMRT*

MWD (r = 0.50*) and %WSA (r = 0.62*). Water stable aggregate percentage was significantly positively correlated with porosity (r = 0.53*), moisture content at 10% air filled porosity (r = 0.53*) but negatively correlated with moisture content at 2 M Pa penetration resistance (r = 0.53*).

Conclusions

We concluded that there was improvement in soil structure under crop residue mulching as evident from higher values of MWD, %WSA and WSSI. Application of irrigation and recommended dose of N also improved soil structural indices. The BD at 0-5 and 5-15 cm soil depth were significantly lower and

Table 8. Interrelationship between maize yield, root growth and soil physical indices

	Sindex	LLWR	BD	FC	PWP	AWC	SHC	MWD	WSA	GMD	WSSI	Porosity	qafp	θ2MPa	RLD	RMD	GY	BY
S index	1.00																	
LLWR	0.01	1.00																
BD	0.11	-0.31	1.00															
FC	-0.17	-0.25	0.15	1.00														
PWP	0.46	-0.20	0.77	0.21	1.00													
AWC	-0.33	-0.18	-0.11	0.94**	-0.13	1.00												
SHC	0.37	-0.21	-0.09	-0.14	0.19	-0.21	1.00											
MWD	-0.19	0.50*	-0.77**	0.31	-0.55*	0.50*	-0.16	1.00										
WSA	-0.32	0.09	-0.53*	0.44	-0.48*	0.62**	0.11	0.54*	1.00									
GMD	0.13	-0.15	-0.26	-0.17	-0.42	-0.02	-0.03	0.05	0.04	1.00								
WSSI	0.01	-0.06	-0.35	0.34	-0.25	0.43	-0.12	0.29	0.71**	0.37	1.00							
Porosity	-0.11	0.31	-1.00	-0.15	-0.77**	0.11	0.09	0.77**	0.53*	0.26	0.35	1.00						
θafp	-0.11	0.31	-1.00	-0.15	-0.77**	0.11	0.09	0.77**	0.53*	0.26	0.35	1.00	1.00					
θ2MPa	0.11	-0.31	1.00	0.15	0.77**	-0.11	-0.09	-0.77**	-0.53*	-0.26	-0.35	-1.00	-1.00	1.00				
RLD	0.45*	-0.02	0.19	-0.24	0.25	-0.33	0.50*	-0.33	-0.27	-0.26	-0.61	-0.19	-0.19	0.19	1.00			
RMD	0.36	-0.19	0.13	-0.23	0.36	-0.36	0.55*	-0.44	-0.14	-0.36	-0.35	-0.13	-0.13	0.13	0.80**	1.00		
GY	0.32	-0.28	0.03	-0.09	0.33	-0.20	0.67**	-0.20	-0.26	0.10	-0.35	-0.03	-0.03	0.03	0.49*	0.63**	1.00	
BY	0.35	-0.14	0.15	-0.18	0.45	-0.34	0.52*	-0.30	-0.40	0.03	-0.40	-0.15	-0.15	0.15	0.50*	0.68**	0.95**	1.00

*indicates significantly correlated at $p < 0.05$; ** indicates significantly correlated at $p < 0.01$

saturated hydraulic conductivity was significantly higher under crop residue mulch than without mulch treatment. Mulching favoured lower values of penetration resistance (PR) at 0-14 cm soil depth. The *S* index and LLWR, which are important soil physical quality parameters, increased due to irrigation, crop residue mulch and N application. There was improvement in root growth, grain and biomass yield of maize under mulching, irrigation and N application. The root growth, grain and biomass yield of maize was significantly correlated with the saturated hydraulic conductivity of soil at 0-15 cm soil depth. Therefore, growing maize crop with need based irrigation at critical crop growth stages, N application @ 150 kg ha^{-1} and wheat residue mulching @ 10 t ha^{-1} resulted in better soil physical quality and higher crop yield in a sandy loam soil of Indo Gangetic plain of India as well as in the adjoining region with similar soil types.

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