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Analysis of soil compaction induced beneath the working depth due to tilling action of different active tillage machinery

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Abstract

Aim of study: To quantify the data regarding soil compaction induced beneath the tillage working depth purely due to the tilling action of the different active tillage machinery in sandy loam soil.

Area of study: Research Farm, CCS Haryana Agricultural University, Hisar, Haryana, India.

Material and methods: The data were quantified in terms of cone index (CI), bulk density, and porosity. Its comparison was also made with conventional practice followed by the farmers, involving only passive-tillage tools (i.e. cultivator and disc harrow). The results did not represent the tractor-imposed soil compaction under the tires.

*Main results:*The maximum soil compaction beneath the working depth in terms of increment in soil CI occurred with rotavator followed by conventional practice, PTO-operated disc tiller, and power harrow, which are in the range of 6.67-7.05%, 5.17-5.29%, 4.29-4.97%, and 2.08-2.36%, respectively. The increment in bulk density was similar to that as mentioned above with values in the range of 3.96-4.06%, 2.30-2.42%, 1.71-1.88%, and 1.31-1.40%, respectively. Furthermore, the maximum decrement in soil porosity occurred with rotavator followed by conventional practice, PTO-operated disc tiller, and power harrow which were in the range of 5.67-6.61%, 2.74-2.94%, 1.71-1.88%, and 2.06-2.25%, respectively.

Research highlights: The active tillage rotary machinery cause soil compaction due to the applied compressive force on the soil during their tilling action. They create optimal topsoil tilth but can compact deeper soil due to blade speed, necessitating the selection of ideal rotational and forward speeds to minimize this compaction.

Additional key words: rotavator; power harrow; PTO disc tiller; cone index; bulk density.

Abbreviations used: BD (bulk density); CI (cone index); db (dry basis); DMR (Duncan's Multiple Range); MWD (mean weight diameter); PTO (power take-off).

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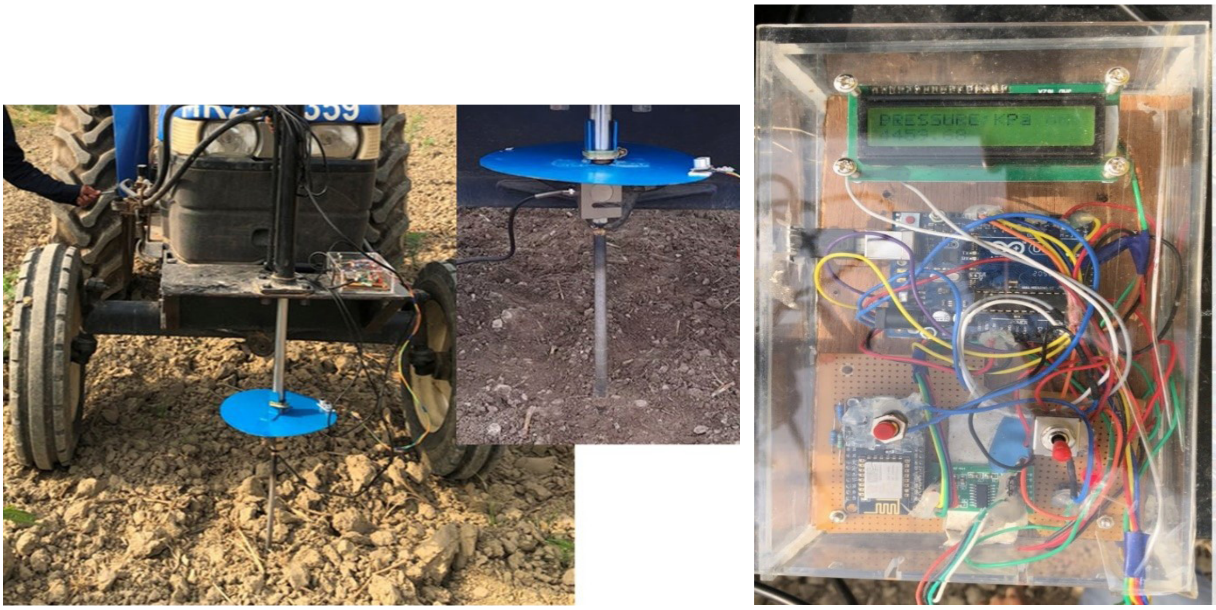
Introduction

The active tillage rotary machinery in which the rotating tools/elements gets powered by the tractor power take-off (PTO) shaft generally cause soil compaction beneath the tillage depths due to the applied compressive force on the soil during their tilling action (Whitefield, 2004; Batey, 2009; Upadhyay & Raheman, 2019). Singh et al. (2015) reported that the excessive use of the rotary plough, especially with an L-blade for many years, caused compaction of soil and formation of the hardpan, which can affect the crop growth and production. Numerous studies have



a) b)

Figure 1. Views of the tractor hydraulic assisted microprocessor-based cone penetrometer: a) sensing unit; b) embedded microprocessor-based unit.

investigated the performance and energy consumption of various active tillage machines (Upadhyay & Raheman, 2018 & 2020; Hensh et al., 2021a; Nataraj et al., 2021). However, data regarding freshly induced soil compaction beneath the tillage depth due to the tilling action of different active tillage machinery in terms of soil parameters such as cone index (CI), bulk density (BD), and porosity are limited and need to be quantified. This led us to conduct a study on freshly induced soil compaction beneath the tillage working depth purely due to the tilling action of the active machinery such as rotavator, power harrow, and PTO-operated disc tiller.

Soil compaction is a major concern for agricultural field management which can either positively or negatively affect plant growth and crop yield (Chen & Weil, 2011; Sarkar et al., 2021; Nisha et al., 2023). Compacted soil can ruin the soil structure, limit air and water infiltration, decrease porosity and increase soil BD and strength, if the soil volume exceeds the penetrometer resistance of 2.5 MPa (Tarawally et al., 2004). These effects have hazardous consequences on air and water infiltration through the root zone depth and impede root growth to cover larger soil areas (Botta et al., 2006; Zhang et al., 2006). The dry BD, void ratio, specific volume, and porosity have all been used to determine soil compaction. Among various soil conditions, one of the keys to off-road vehicle performance is a correct assessment of the terrain's strongest attributes. Soil penetration resistance and shear stress are two strength qualities that limit machine movement by limiting potential traction and crop yield (Akhtar et al., 2021). Extreme soil compaction and electrical conductivity harm agriculture and soil environment (Singh et al., 2015). The compacted soil cannot be alleviated by the usual tillage practice and remains for more than one year causing reduced root development (Raper & Mac Kirby, 2006). Many researchers have worked on the effects of subsoil compaction and tillage methods to control the hardpan (Birkas et al., 1998; Gemtos et al., 1998; Sarkar et al., 2021).

Soil compaction can be caused by various farming practices such as tillage, that removes the protective residue from the soil surface, leaving soil prone to natural environmental factors or excessive soil tillage which degrades the soil. Compaction that develops on the surface of the tillage field is called surface compaction, whereas the compaction that occurs due to the surface load below the tillage layer is termed as subsoil compaction (Reddy, 2016). Heavy tillage machinery may induce some soil compaction just below the depth of tillage, particularly when the soils are wet. Generally, soil compaction may be induced at intervals of twenty four inches of the topsoil (Muckel, 2004). The type and size of the implement, contact area and inflation pressure of the tyre, soil type, and water content are the major factors affecting the compaction of soil (Smith et al., 1997; Hamza & Anderson, 2005). Soil compaction is also caused by repeated passes of primary and secondary tillage required for preparing the seedbed, resulting in a reduced crop yield (Shah et al., 2017; Kumar et al., 2023a). Reddy (2016) reported that soil compaction has also some other effects such as affecting the soil's water-holding capacity, water infiltration, water redistribution over landscapes, and the roots' ability to extract water (slow root growth), poor drainage of the soil, and restriction of nitrogen and other nutrients uptake.

The specific objective of this study was to quantify the data regarding freshly induced soil compaction beneath

Table 1. Implements used in the study.

Implement	Type of soil cutting element	No. of soil cutting elements	Adjacent spacing between soil cutting elements, mm	Working width, mm	Rotational speed of tillage element, rpm	Overall weight, kg
Rotavator	L-shaped blades	36 (7 rotor flanges)	240	1524	250	410
Power harrow	Vertical tine blades	14 (7 rotor flanges)	220	1710	285	545
PTO-operated disc tiller	Plain concave discs	8	215	1600	170	452
Cultivator (rigid-tyne)	Reversible shovels/tynes	9	232	1900	na	255
Disc harrow (offset type)	Plain concave discs	16	225	1800	na	337

na: not applicable.

the tillage working depth purely due to the tilling action of the active machinery such as rotavator, power harrow, and PTO-operated disc tiller in sandy loam soil. The data were quantified in terms of soil compaction parameters such as CI, BD, and porosity. It was also compared with the conventional tillage practice followed by the farmers involving only passive-tillage tools (i.e. cultivator and disc harrow).

Material and methods

Experimental plan for the field tests

Field experiments were conducted at the Research Farm of the Deendayal Upadhyaya Centre of Excellence for Organic Farming, CCS Haryana Agricultural University, Hisar, Haryana, India. The soil texture at the experimental site is classified as sandy loam with no previous crop residue present on the surface. The objective of the field tests was to analyze the freshly induced soil compaction beneath the tillage working depth purely due to the tilling action under different active tillage treatments. Field tests were completely randomized with four treatments at three different test sites. The active tillage implements considered in this study for different treatments were rotavator, power harrow, and PTO-operated disc tiller. The different tillage treatments considered were T1 (1 × rotavator), T2 (1 × power harrow), T3 (1 × PTO-operated disc tiller), and T4 (1 × Cultivator + 2 × Disc harrow). T4 was a conventional tillage treatment generally followed by the farmers to prepare the seedbed which involves a single pass of a cultivator followed by two passes of an offset disc harrow. Before initiating the field tests, the soil parameters such as moisture content, CI, BD, and porosity were measured in each experimental plot at two soil profile layers i.e. 0-120 mm and 120-220 mm depth ranges, to ensure the uniformity of the test sites for conducting the experiments. The criteria for selecting the 0-120 mm depth range was based on the maximum achievable depth under different tillage treatments which were observed to be 120 mm.

Implements description

The major specifications of the different active tillage implements used in the study are given in Table 1. The rotavator was equipped with L-shaped blades having an average working width of 1524 mm with a total of seven rotor flanges (horizontal axis). The power harrow had seven rotor flanges (vertical axis) with an overall working width of 1710 mm. Each rotor flange was equipped with two vertical tine blades having lengths and thicknesses of 285 and 12 mm, respectively. The PTO-operated disc tiller consisted of eight actively rotating plain concave discs mounted in a single gang with spacing between adjacent discs of 215 mm. The cultivator was a rigid-tyne type having nine furrow openers at 235.5 mm spacing. The trailed type offset disc harrow consisted of eight concave discs in each gang with spacing of 225 mm between adjacent discs.

The cultivator and offset disc harrow were successfully operated in transmission gear L3, while the rotavator, power harrow, and PTO-operated disc tiller required transmission gear L1 for satisfactory operation during tillage. The treatment T1 comprised a single pass of the rotavator; its actual forward speed of operation and rotor speed were 2.23 km h^{-1} and 250 rpm, respectively. T2 involved a single pass of power harrow at forward speed and rotor speed of 2.11 km h^{-1} and 215 rpm, respectively. T3 applicated a single pass of PTO-operated disc tiller at forward speed and rotational speed of the front gang axle of 2.19 km h^{-1} and 170 rpm, respectively. In T4, the seedbed was prepared by operating a single pass of cultivator followed by the two passes of offset disc harrow to achieve the desired tilth for seedbed preparation; their actual forward speeds achieved in transmission gear L3 with the cultivator and disc harrow were 5.47 and

6.33 km h^{-1}, respectively. The implement weight per unit width of operation for rotavator, power harrow, PTO-operated disc tiller, cultivator, and offset disc harrow were 269.7, 318.7, 282.5, 134.2, and 187.2 kg m^{-1}, respectively.

The residue of various cereal and pulses crops can be effectively mixed with soil using active tillage rotary implements in contrast to passive type implements, which generally bury it into the soil. Recently, the development of machinery such as Super Seeder, allows residue incorporation and seeding operations in one go, and make the residue incorporation method more feasible. Super Seeder is equipped with a rotavator fitted with 'LJF' blades at the front, followed by sowing and compaction units at the rear. The shape of 'LJF'-type blades gives the benefit of gradual increment in bite-width as opposed to constant bite-width in traditional 'L'-type blades in rotavators during their impact on the ground (Kumar et al., 2023b & 2023c). As the compaction tests were carried out in plots having no previous crop residue present on the surface, we did not use Super Seeder in any treatment. However, it could be considered for future studies.

Measurement of soil parameters

Measurement of soil moisture content

The moisture content of the soil before the tillage operation was determined by the standard oven drying method. For each treatment, the soil samples were collected from two soil profiles (i.e. 0-120 mm and 120-220 mm) at three random locations within a particular strip. The wet weight of each sample was recorded. Thereafter, the samples were placed in the oven for 24 hours at 105 ºC and weights of dried samples were recorded.

Measurement of soil cone index (CI)

The soil CI was measured with the help of a tractor hydraulic-assisted embedded microprocessor-based cone penetrometer (Fig. 1), capable of recording the data of soil CI and depth of penetration with less human engagement and errors. The penetrometer consisted of a driving system, a sensor unit for measuring the force required to push the probe into the soil and depth of penetration, and a data logging system (Nisha et al., 2023). The selected control valves installed between the tractor hydraulic system and the hydraulic cylinder helped to achieve a desired penetration speed of 30 mm s^{-1}. A standard cone penetrometer probe with a cone having base diameter 20.30 mm, shaft diameter 15.90 mm, cone base area 323 mm^2, and an apex angle of 30° was used. The sensing unit of the developed system consisted of an industrial S-type load cell of 500-kg capacity fitted between the threaded end of the cylinder rod and cone penetrometer rod to measure the penetration resistance. The depth of penetration was measured using an ultrasonic sensor mounted beneath a circular plate fixed in the cylinder rod. The ultrasonic sensor had a sensing range of 20 to 4000 mm with a sensing angle of 15° and was accurate to the nearest 30 mm. A WiFi module transmitted the acquired data with the help of the microprocessor unit to a mobile application developed in the Android platform.

The accuracy and non-linearity of the soil penetration resistance measurement unit were 1.85% and 0.69%, respectively. The accuracy and non-linearity of the penetration depth measurement unit were 1.90% and 0.55%, respectively (Liu et al., 2018; Hensh et al., 2021b; Upadhyay et al., 2022). The repeatability of the soil penetration resistance and penetration depth measurement units was 0.37% and 0.52%, respectively (Liu et al., 2018; Hensh et al., 2021b; Upadhyay et al., 2022).

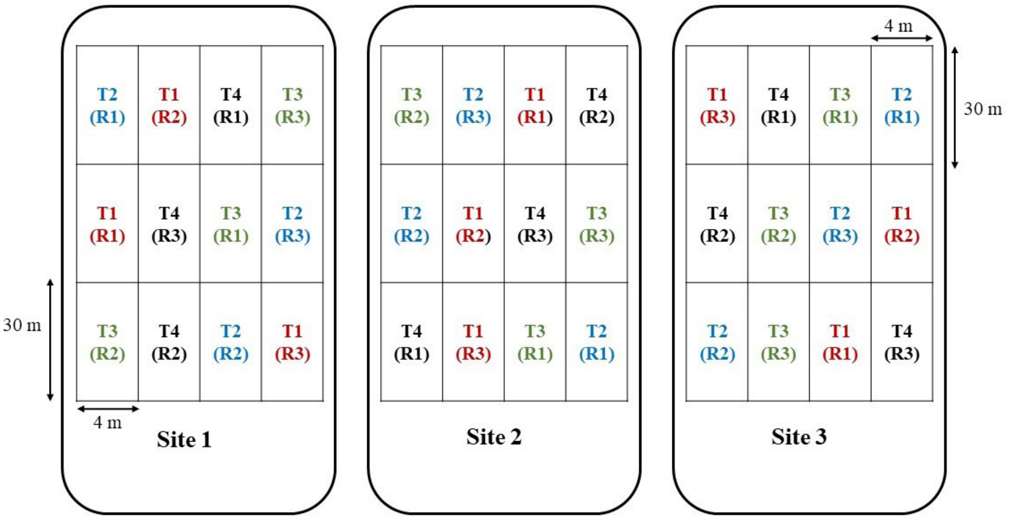
The average CI of the soil beneath the working depth (i.e. 120-220 mm depth range) was measured before and after each tillage treatment. For each tillage treatment, soil CI was measured at five random locations, and the average was calculated for the two considered depth ranges. The percentage increment in soil CI beneath the working depth was calculated with respect to soil CI of the test strip before tillage, which indicates any freshly induced soil compaction beneath the working depth purely due to the tilling action of the implement.

Measurement of soil bulk density (BD)

The soil BD was determined with the help of a core cutter sampler of diameter 100 mm and height 130 mm. The core sampler was inserted vertically into the soil and a core was carefully extracted without disturbance. Further, the core samples were placed in a 105 °C hot air oven for 24 hours until thoroughly dried, after which these samples were weighed (ASA, 1965). The resulting weight was used for calculating the dry BD of the soil. The average BD of the soil beneath the working depth (i.e. 120-220 mm depth range) was measured before and after each tillage treatment. For each tillage treatment, soil BD was measured at three random locations, and the average was calculated for the two considered depth ranges. The increment in soil BD beneath the working depth was calculated with respect to BD of the test strip before tillage, which indicates any freshly induced soil compaction beneath the working depth purely due to the tilling action of the implement.

Measurement of soil porosity

The porosity of the soil or pore space is defined as the volume of soil voids that can be filled by water and/or air. It has an inverse relationship with BD. Porosity is expressed as a percentage of the total volume of the soil. Many studies on the impact of the tillage traffic compaction on the porosity and structure of various soils have found a strong link between soil porosity and penetration



Site 1

T2 (R1)	T1 (R2)	T4 (R1)	T3 (R3)
T1 (R1)	T4 (R3)	T3 (R1)	T2 (R3)
T3 (R2)	T4 (R2)	T2 (R2)	T1 (R3)

Site 2

T3 (R2)	T2 (R3)	T1 (R1)	T4 (R2)
T2 (R2)	T1 (R2)	T4 (R3)	T3 (R3)
T4 (R1)	T1 (R3)	T3 (R1)	T2 (R1)

Site 3

T1 (R3)	T4 (R1)	T3 (R1)	T2 (R1)
T4 (R2)	T3 (R2)	T2 (R3)	T1 (R2)
T2 (R2)	T3 (R3)	T1 (R1)	T4 (R3)

Treatments: T1 (1 × rotavator); T2 (1 × power harrow); T3 (1 × PTO-operated disc tiller); T4 (1 × Cultivator + 2 × Disc harrow)
R = Replication

Figure 2. Experimental layout of the tests performed.

resistance (Pagliai & De Nobili, 1993; Marsili et al., 1998). The average porosity of the soil beneath the working depth (i.e. 120-220 mm depth range) was measured before and after each tillage treatment. For each tillage treatment, soil porosity was measured at three random locations, and the average was calculated for the two considered depth ranges. The % decrement in soil porosity beneath the working depth was calculated with respect to porosity of the test strip before tillage, which indicates any freshly induced soil compaction beneath the working depth purely due to the tilling action of the implement. The particle density was determined using the pycnometer method. According to Carter & Gregorich (2007), the average particle density of agricultural soils is about 2.65 g cm^{-3}.

Measurement of soil pulverization

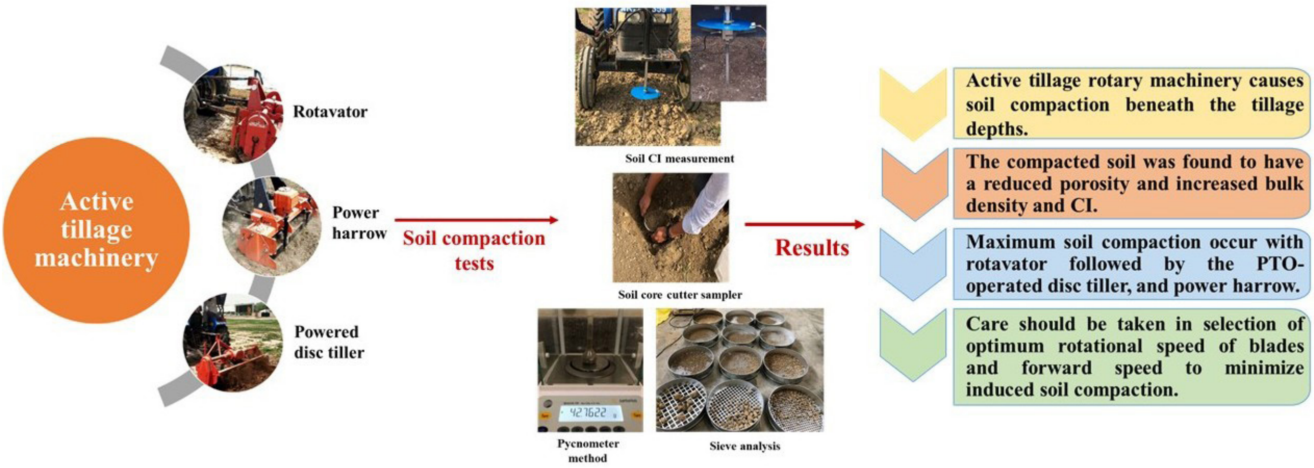
Soil pulverization was quantified in terms of the mean weight diameter (MWD) of soil aggregates using a mechanical sieve shaker, following the methods prescribed by Smith et al. (1994). A set of 11 sieves of size 31.5, 19.0, 13.2, 9.5, 8.0, 5.6, 4.75, 3.35, 2.0, 1.4, and 1.0 mm were used for the test. Sieve analysis was carried out by carefully collecting soil samples from randomly selected areas of 1×1 m up to the tillage working depth in collecting bags to find the MWD of the clods. Before performing the sieve analysis, the samples were naturally dried for 24 hours and a column of sieves with a gradual decrease in mesh sizes was introduced on a mechanical sieve shaker. The mean size of clods retained on the largest aperture sieve was determined by measuring the clod's dimensions in principal planes. The weight of the soil retained on each sieve was measured with the help of an electronic balance. Three replications were taken for each tillage treatment within the test run, and the average MWD of soil clods in mm was computed.

Measurement of operating parameters

To determine the forward speed of operation, a length of 25 m was marked with the ranging rods, and the tractor with the implement was operated in the test run. A stopwatch was used to record the time for the operation to traverse the marked run and the forward speed of the operation was computed (Rasool et al., 2017; Upadhyay et al., 2017). The depth of the operation under the different treatments was calculated by measuring the distance between furrow sole and ground level using a scale along the furrow wall at an interval of about 3 m along the length of the furrow. The average of five readings was calculated to determine the depth of the operation under the different treatments. The rotational speed of PTO shaft was measured with the help of a laser tachometer. A reflecting paper was placed on the PTO shaft and the tractor engine was operated. The tachometer sensed the reflection from the reflector and gave the rotational speed of the PTO shaft. The rotational speed of the tillage tool was determined after considering the gear ratio from PTO input shaft to the rotor shaft.

Experimental procedure for the field tests

All the experiments were conducted with a 29 kW 2WD tractor (New Holland 4010) at three different test sites: Site 1 (29.13654° N, 75.69817° E), Site 2 (29.13644° N, 75.69817° E), and Site 3 (29.1504° N, 75.7057° E). The experimental layout is presented in Fig. 2. Each test site was divided into 12 strips (four treatments and three replications) for the comparative study of different tillage treatments. A completely randomized block design was followed for carrying out the soil compaction experiments. Each test was conducted over an approx. 30 m test strip. Before conducting each test, soil samples were randomly collected from the test



Active tillage rotary machinery causes soil compaction beneath the tillage depths.

The compacted soil was found to have a reduced porosity and increased bulk density and CI.

Maximum soil compaction occur with rotavator followed by the PTO-operated disc tiller, and power harrow.

Care should be taken in selection of optimum rotational speed of blades and forward speed to minimize induced soil compaction.

Figure 3. Graphical abstract of the soil compaction research.

strip to determine the moisture content, BD, porosity, and CI of the soil before tillage operation. The moisture content of the soil was measured to ensure the uniformity of different test strips for conducting the compaction tests.

Thereafter, each implement in the respective treatment was operated at a suitable forward speed and recommended rotor/gang axle speed. The forward speed of the tractor was varied by selecting the appropriate transmission gear and the throttle position of the tractor was set to maintain a PTO speed of 540±40 rpm during all the tests. The average operating depth under all treatments was maintained as 120±10 mm. After the tillage treatments, the soil compaction parameters such as CI, BD, and porosity of the soil were again measured beneath the working depth (i.e. 120-220 mm depth range) in that particular operation. The data were analyzed in terms of % increment or decrement in these parameters beneath the working depth with respect to their values before tillage, in order to identify any freshly induced soil compaction beneath the working depth purely due to the tilling action of the implement. The data should not include the tractor-imposed soil compaction under the tires, so we carefully measured the soil parameters about 200 mm distant from the inner ends of tractor tires. Further, the data regarding soil pulverization in terms of MWD of soil aggregates were also determined to assess the quality of the tilled soil under different tillage treatments. The graphical abstract of the soil compaction research is presented in Fig. 3.

Statistical analysis of the data

Statistical analysis was also performed on the acquired data using SPSS 22.0 software. Analysis of variance (ANOVA) was carried out to check the significance of different tillage treatments on measured soil compaction parameters i.e. CI, BD, and porosity of the soil beneath

Table 2. Soil moisture content (%, dry basis) of different test sites measured before the tillage operation.

Treatments	Test site 1	Test site 2	Test site 3
	Depth of observation = 0-120 mm		
T1 (1 × Rotavator)	12.15 ± 0.31^{a}	12.10 ± 0.27^{a}	11.98 ± 0.82^{a}
T2 (1 × Power harrow)	12.12 ± 0.61^{a}	12.38 ± 0.10^{a}	11.74 ± 0.65^{a}
T3 (1 × Powered disc tiller)	12.04 ± 0.23^{a}	12.17 ± 0.55^{a}	12.15 ± 0.64^{a}
T4 (1 × Cultivator + 2 × Disc harrow)	11.84 ± 0.43^{a}	12.96 ± 0.54^{b}	11.94 ± 0.18^{a}
	Depth of observation = 120-220 mm		
T1 (1 × Rotavator)	15.01 ± 0.04^{a}	15.17 ± 0.56^{a}	15.19 ± 0.23^{a}
T2 (1 × Power harrow)	15.90 ± 0.48^{b}	15.78 ± 0.36^{a}	15.69 ± 0.35^{b}
T3 (1 × Powered disc tiller)	15.31 ± 0.33^{b}	15.57 ± 0.65^{a}	15.26 ± 0.22^{b}
T4 (1 × Cultivator + 2 × Disc harrow)	15.80 ± 0.18^{b}	15.99 ± 0.13^{a}	15.72 ± 0.06^{b}

Mean values along the same column for individual test sites and depth of observation followed by different letters are significantly different at 5% level of significance according to Duncan's multiple range tests.

Table 3. Average values of mean weight diameter (MWD) of soil aggregates under different tillage treatments.

Treatments	MWD of soil aggregates, mm		
	Test site 1	**Test site 2**	**Test site 3**
T1	4.25 ± 0.26^{a}	4.21 ± 0.07^{a}	4.29 ± 0.33^{a}
T2	7.25 ± 0.08^{b}	7.26 ± 0.36^{b}	7.02 ± 0.22^{b}
T3	13.80 ± 0.13^{c}	13.64 ± 0.16^{c}	13.91 ± 0.34^{c}
T4	11.95 ± 0.20^{d}	11.79 ± 0.11^{d}	11.83 ± 0.20^{d}

Mean values along the same column for individual test sites followed by different letters are significantly different at 5% level of significance according to Duncan's multiple range tests.

the tillage depth at a 5% level of significance. Duncan’s multiple range (DMR) tests were also carried out to check the existence of significant treatment differences between the means of % increment in soil compaction beneath the working depth in terms of CI, BD, and porosity of the soil at a 5% level of significance.

Results and discussion

Soil properties of the test sites measured before conducting soil compaction tests

The data on the moisture content of the soil measured at a depth of 0-120 mm and 120-220 mm before the tillage operation at different test sites are given in Table 2. The average moisture content of the soil profile at a depth of 0-120 mm varied from 11.84 to 12.15% (db), 12.10 to 12.96%, and 11.74 to 12.15% at test sites 1, 2, and 3, respectively. The results of DMR tests indicated that the differences in the moisture content of soil at a depth range of 0-120 mm under most of the tillage treatments (except in T4 at site 2) were statistically non-significant ($p \leq 0.05$) for the three test sites.

The average moisture content of the soil at a depth range of 120-220 mm varied from 15.01 to 15.90% (db), 15.17 to 15.99%, and 15.19 to 15.72% at test sites 1, 2, and 3, respectively. Moreover, the results of the DMR tests indicated that the differences in the soil moisture content under the treatments (except in T1 at sites 1 and 3) were statistically non-significant ($p \leq 0.05$) for the three sites.

Table 4. Soil cone index (CI) values measured beneath the working depth (120-220 mm) under different treatments. Values are mean ± std. dev.

Treatments	Soil CI, kPa		Increment in CI, %
	Before tillage operation (CI_{Before})	**After tillage operation (CI_{After})**	$\frac{(CI_{After}\ \ CI_{Before})}{CI_{Before}}\times 100$
		Test site 1	
T1	2678 ± 72.42^{a}	2860 ± 71.09	6.79 ± 0.32^{a}
T2	2807 ± 75.89^{b}	2865 ± 75.60	2.08 ± 0.14^{b}
T3	2795 ± 75.56^{b}	2922 ± 76.49	4.57 ± 0.11^{c}
T4	2671 ± 72.21^{a}	2809 ± 77.34	5.17 ± 0.07^{d}
		Test site 2	
T1	2515 ± 67.99^{b}	2692 ± 72.67	7.05 ± 0.21^{a}
T2	2317 ± 62.65^{a}	2372 ± 64.93	2.36 ± 0.18^{b}
T3	2575 ± 69.62^{b}	2697 ± 75.03	4.74 ± 0.11^{c}
T4	2488 ± 67.27^{b}	2620 ± 68.70	5.29 ± 0.35^{d}
		Test site 3	
T1	2875 ± 77.72^{a}	3066 ± 79.12	6.67 ± 0.31^{a}
T2	2915 ± 78.81^{a}	2980 ± 77.15	2.24 ± 0.16^{b}
T3	2815 ± 76.12^{a}	2936 ± 77.72	4.29 ± 0.22^{c}
T4	2810 ± 75.98^{a}	2950 ± 75.05	4.97 ± 0.19^{d}

Mean increments along the same column for individual sites followed by different letters are significantly different at 5% level of significance according to Duncan's multiple range tests.

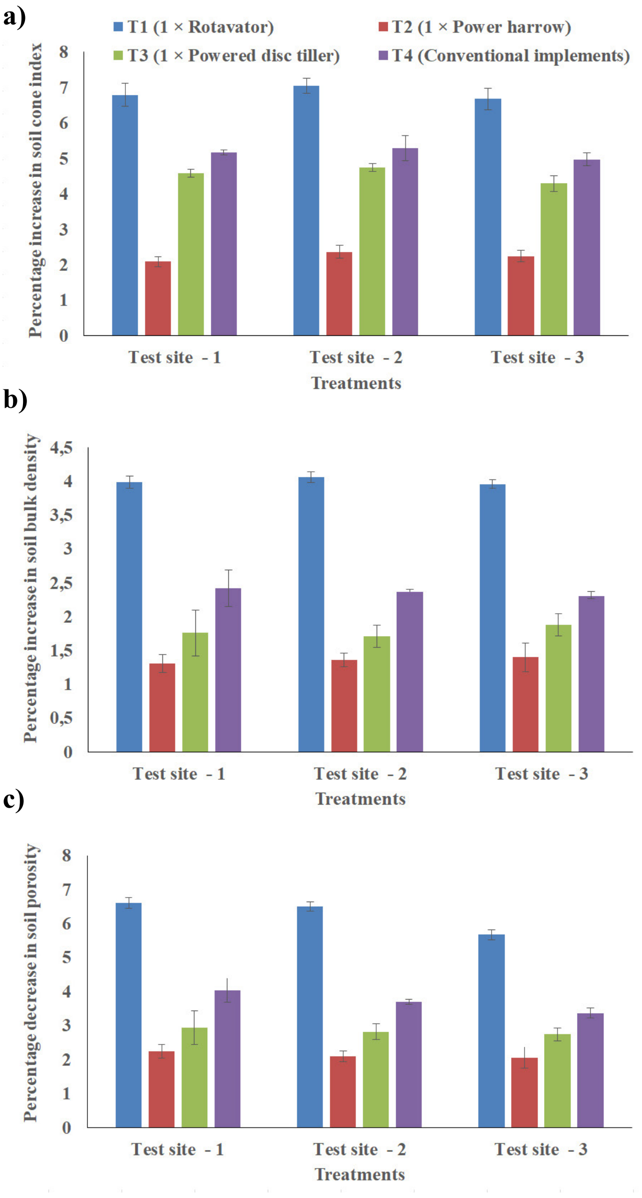


Figure 4. Effect of different tillage treatments on soil compaction parameters: a) increase in soil cone index (%); b) increase in soil bulk density (%); c) decrease in soil porosity (%).

All these data indicated uniform soil moisture profiles for conducting the compaction tests.

Soil pulverization or mean weight diameter (MWD) of the soil aggregates

It is to be noted that the soil pulverization in terms of MWD of the soil aggregates was determined to assess the quality of the tilled soil under different tillage treatments to analyze the suitability of test beds for immediate sowing, and this parameter is not related to any induced soil compaction. The results on soil pulverization or MWD of the soil aggregates observed after the tillage treatments are presented in Table 3. It is evident from Table 3 that soil pulverization significantly varied with the tillage treatments followed. The smallest MWD of the soil aggregates or maximum soil pulverization was obtained in T1 (4.25 mm), followed by T2 (7.25 mm), T4 (11.95 mm) and T3 (13.80 mm) at site 1. Similar results were observed at the other sites (Table 3). DMR tests results indicate that the effect of different tillage treatments on soil pulverization were statistically significant at 5% level of significance for all three test sites.

The clod sizes should be the in the ideal range; too fine soil causes soil erosion and requirement of higher energy demand to pulverize the soil, while too large clods affect the sowing operations and harm plant growth. After following all the tillage treatments, the test bed was found to be suitable for sowing operation. Ahmad et al. (2010) analyzed the tillage quality of different tillage treatments i.e. conventional rotavator (T1), modified rotavator (T2), spade cultivator (T3), chisel plough + rotavator (T4), and chisel plough with modified rotavator (T5). They reported highest soil pulverization under treatment T4 followed by T5, T2, T1, and T3, indicating that the use of rotavator produces finer particles than spade cultivator. Bhusan (1971) reported that different tillage practices have an impact on the distribution of clod sizes. According to his study, disc and moldboard ploughs produced a higher percentage of clods with a diameter greater than 52 mm. Choudhary et al. (2021) assessed the tillage quality of different treatments i.e. T1 (1 × cultivator + 2 × offset disc harrow), T2 (1 × combined offset disc harrow), T3 (1 × cultivator + 1 × single rotor type rotavator), T4 (1 × double rotor type rotavator), and T5 (1 × power harrow). They reported highest soil pulverization under treatment T4 followed by T3, T5, T1, and T2.

Analysis of the tillage-induced soil compaction under different tillage treatments

The soil compaction induced under different tillage treatments was analyzed in terms of % increase in CI and BD, and % decrease in the porosity of the soil beneath the respective working depths. It is worth mentioning that the presented results on soil compaction are purely induced by the tilling action of different tillage treatments during multiple passes and do not include the tractor-imposed soil compaction under the tires. The results of tillage-induced soil compaction under different tillage treatments are presented in the following sub-sections.

Effect of different tillage treatments on soil cone index (CI) beneath the tillage depth

The readings on soil CI were taken before and after the tillage operation beneath the working depth (120-

Table 5. ANOVA results for soil cone index values observed beneath the working depth (120-220 mm) after tillage operation with different treatments.

Source	df	Site 1			Site 2			Site 3		
		Mean square	F value	Sig.	Mean square	F value	Sig.	Mean square	F value	Sig.
Corrected model	3	19.16	598.7	<0.001	18.49	377.3	<0.001	16.68	313.3	<0.001
Intercept	1	432.45	13514.1	<0.001	476.29	9720.2	<0.001	414.05	7775.6	<0.001
Treatment	3	19.16	598.7	<0.001	18.49	377.3	<0.001	16.68	313.3	<0.001
Error	16	0.03			0.05			0.05		
Total	20									
Corrected total	19									

$R^2 = 0.99$ (Adjusted $R^2 = 0.99$); df: degrees of freedom; F-value: index of significance of the coefficient of determination.

220 mm) at three different test sites. For each test site, soil CI readings were measured and averaged for five random locations under each treatment and the results are given in Table 4. The average CI of the soil beneath the working depth (120-220 mm) before the tillage operation varied from 2670.89 to 2806.86 kPa, 2317.21 to 2574.89 kPa, and 2810.40 to 2915.05 kPa at test sites 1, 2, and 3, respectively. Further the results of DMR tests indicate that the differences in the CI of soil beneath the working depth before the tillage operation under most of the tillage treatments were statistically non-significant ($p \leq 0.05$) for the three sites indicating uniform field conditions for carrying out the compaction tests. ANOVA tests (Table 5) carried out on the data of soil CI observed beneath the working depth (120-220 mm) after tillage operation with different treatments, indicated that at all test sites, the CI beneath the tillage depth observed after tillage operation was significantly affected by the tillage treatments.

The data were analyzed in terms of % increments in the CI beneath the tillage depth under different tillage treatments and the results are presented in Table 4 and plotted in Fig. 4(a). It is clear that, at test site 1, the maximum % increment in soil CI beneath the working depth (or soil compaction) was observed in T1 (6.79 ± 0.32%) followed by T4 (5.17 ± 0.07%), T3 (4.57 ± 0.11%), and T2 (2.08 ± 0.14%) with respect to CI of the soil before operation. Similar results were observed at test sites 2 and 3 with average % increment in CI of 7.05 ± 0.21%, 2.36 ± 0.18%, 4.74 ± 0.11%, and 5.29 ± 0.35% at test site 2; and 6.67 ± 0.31%, 2.24 ± 0.16%, 4.29 ± 0.22%, and 4.97±0.19% at test site 3 under treatments T1, T2, T3, and T4, respectively. DMR tests indicated that the effect of different tillage treatments on soil CI were statistically significant 5% level of significance for the three test sites.

The higher CI values observed after tillage operation under all treatments indicate the possibility of freshly induced soil compaction beneath the tilled layer due to the tilling action of the tools and the weight of the implement. The possible explanation for T1 showing a higher % increase in soil CI beneath the tillage depth could be due to the greater impact force exerted by the rotation of the blades of the rotavator on the soil while travelling horizontally at the bottom of their stroke, as stated by Whitefield (2004), Ahmad et al. (2010) and Upadhyay & Raheman (2019). Treatment T2, which includes a single pass of power harrow, shows the lowest increment in soil CI beneath the tillage depth. This could be due to the vertical rotation of the blades exerting less downward impact force on the soil profile. Similar results for the change in CI after tillage treatments were also reported in different studies conducted by Hamza & Anderson (2005), and Jabro et al. (2008). Upadhyay & Raheman (2019) observed the highest % increase in CI beneath the tillage depth with rotavator followed by powered and free rolling modes of a disc harrow with respect to CI of the field before operation. Their results indicate that active tillage machines cause more soil compaction for the same operating conditions as compared to conventional passive type tillage implements. According to Meyer et al. (1997), the use of a rotary cultivator caused compaction in the 100-200 mm and 200-300 mm soil layers beneath the tillage depth. Ahmad et al. (2010) observed that although rotavator produce fine soil tilth at top soil layers, the high speed rotating action of its blades compact the soil beneath its operational depth.

The treatment T4 showed next higher % increment in soil CI beneath the tillage depth after T1. The possible explanation for this behavior could be the multiple tillage passes (total three) required with the treatment T4 for preparing the seed bed suitable for sowing.

Effect of different tillage treatments on soil bulk density beneath the tillage depth

The readings on soil BD were taken before and after the tillage operation beneath the working depth (120-220 mm) at three different test sites. For each test site, soil BD was measured and averaged for three random locations under each treatment, and the results are shown in Table 6. ANOVA tests carried out on the data of soil BD observed beneath the working depth (120-220 mm) after tillage operation with different treatments (Table 7), indicated that

Table 6. Soil bulk density (BD) values observed 100 mm beneath the working depth (120-220 mm) under different treatments. Values are mean ± std. dev.

Treatments	Soil BD, kg m^{-3}		Increment in BD, %
	Before tillage operation (BD_{Before})	After tillage operation (BD_{After})	$\frac{(BD_{After}\ \ BD_{Before})}{BD_{Before}}\times 100$
Test site 1			
T1	1510 ± 0.00^a	1570 ± 0.01	3.99 ± 0.09^a
T2	1527 ± 0.01^a	1547 ± 0.01	1.31 ± 0.13^b
T3	1513 ± 0.02^a	1540 ± 0.01	1.76 ± 0.34^c
T4	1513 ± 0.01^a	1550 ± 0.01	2.42 ± 0.27^b
Test site 2			
T1	1520 ± 0.00^b	1582 ± 0.00	4.06±0.08^a
T2	1499 ± 0.00^a	1519 ± 0.00	1.36±0.10^b
T3	1536 ± 0.01^c	1563 ± 0.01	1.71±0.16^c
T4	1506 ± 0.01^a	1542 ± 0.01	2.37±0.03^d
Test site 3			
T1	1508±0.01^a	1568±0.01	3.96±0.06^a
T2	1526±0.01^b	1547±0.01	1.40±0.21^b
T3	1519±0.01^b	1547±0.01	1.88±0.16^c
T4	1522±0.01^b	1557±0.01	2.30±0.07^d

Mean increments along the same column for individual sites followed by different letters are significantly different at 5% level of significance according to Duncan's multiple range tests.

at all test sites, the BD beneath the tillage depth observed after tillage operation was significantly affected by the tillage treatments at a 5% level of significance.

The data were analyzed in terms of % increments in the BD beneath the tillage depth under different treatments and the results are presented in Table 6 and plotted in Fig. 4(b). At test site 1, the maximum increment in soil BD beneath the working depth was observed in T1 (3.99 ± 0.09%), followed by T4 (2.42 ± 0.27%), T3 (1.76 ± 0.34%), and T2 (1.31 ± 0.13%) with respect to the BD of the soil before operation. Similar results were observed at test sites 2 and 3, with an average increment in BD of 4.06 ± 0.08%, 1.36 ± 0.10%, 1.71 ± 0.16%, and 2.37 ± 0.03% at test site 2; and 3.96 ± 0.06%, 1.40 ± 0.21%, 1.88 ± 0.16%, and 2.30 ± 0.07% at test site 3 under treatments T1, T2, T3, and T4, respectively. DMR tests were also carried out to check the existence of significant treatment differences between the means of increment in soil compaction beneath the working depth at a 5% level of significance. DMR tests indicate that the effect of different tillage treatments on soil BD beneath the tillage depth were statistically significant for all the test sites.

The higher BD values observed after tillage operation under all treatments indicate the possibility of freshly induced soil compaction beneath the tilled layer due to the tilling action of the tools and the weight of the implement.

Table 7. ANOVA results for soil bulk density (BD) values observed beneath the working depth (120-220 mm) after tillage operation with different treatments.

Source	df	Site 1			Site 2			Site 3		
		Mean square	F value	Sig.	Mean square	F value	Sig.	Mean square	F value	Sig.
Corrected model	3	4.10	83.3	< 0.001	4.22	281.5	< 0.001	3.68	169.7	< 0.001
Intercept	1	67.69	1376.7	< 0.001	67.21	4480.9	< 0.001	67.69	3124.0	< 0.001
Treatment	3	4.10	83.3	< 0.001	4.22	281.5	< 0.001	3.68	169.7	< 0.001
Error	16	0.05			0.01			0.02		
Total	20									
Corrected total	19									

R^2 = 0.97 (Adjusted R^2 = 0.97); df = degrees of freedom; F-value: index of significance of the coefficient of determination.

Table 8. Soil porosity values observed 100 mm beneath the working depth (120-220 mm) under different treatments. Values are mean ± std. dev.

Treatments	Soil porosity, %		Decrement in soil porosity, %
	Before tillage operation (BD_{Before})	After tillage operation (BD_{After})	
Test site 1			
T1	37.62 ± 0.19^a	35.14 ± 0.21	6.61 ± 0.16^a
T2	36.91 ± 0.29^a	36.09 ± 0.24	2.25 ± 0.20^b
T3	37.47 ± 0.63^a	36.36 ± 0.45	2.94 ± 0.50^c
T4	37.47 ± 0.48^a	35.95 ± 0.32	4.04 ± 0.36^d
Test site 2			
T1	38.45 ± 0.07^b	35.95 ± 0.11	6.50 ± 0.14^a
T2	39.31 ± 0.04^c	38.49 ± 0.08	2.09 ± 0.16^b
T3	37.80 ± 0.48^a	36.73 ± 0.44	2.82 ± 0.23^c
T4	39.01 ± 0.26^c	37.57 ± 0.28	3.70 ± 0.08^d
Test site 3			
T1	41.09 ± 0.28^b	38.76 ± 0.32	5.67 ± 0.14^a
T2	40.40 ± 0.23^{ab}	39.57 ± 0.29	2.06 ± 0.32^b
T3	40.67 ± 0.31^a	39.56 ± 0.22	2.74 ± 0.19^c
T4	40.53 ± 0.21^a	39.17 ± 0.26	3.37 ± 0.14^d

Mean values along the same column for individual sites followed by different letters are significantly different at 5% level of significance according to Duncan's multiple range tests.

The BD of the soil was directly correlated with the soil CI value, as also propounded by Kumar et al. (2012). Therefore, the possible reasons behind the trend of higher or lower soil compaction in terms of BD under different tillage treatments are similar to the ones mentioned for soil CI in the above section. Similar results for a greater range of observations concerning BD, hydraulic conductivity, and particle density of the soil were also quoted by Alam et al. (2014), and Blanco & Ruis (2018). In a comparative study conducted by Ahmad et al. (2010), a minimum BD of 1.23 g cm^{-3} was observed after the tillage operation with a spade cultivator at a depth of 200-300 mm, while maximum BD of 1.99 g cm^{-3} was observed with a rotavator indicating higher soil compaction beneath the tilled layers with the use of rotavator. Their results were in agreement with the findings of Lampurlanés & Cantero-Martínez (2003), and Jabro et al. (2008).

Effect of different tillage treatments on soil porosity beneath the tillage depth

The porosity of the soil was calculated based on the relationship between BD and particle density (Danielson & Sutherland, 1986). The average particle density for sites 1, 2, and 3 was 2.42, 2.56, and 2.47 g cm^{-3}, respectively. The readings on soil porosity were taken before and after the tillage operation beneath the working depth (120-220 mm) at the three test sites. Table 8 shows that the average porosity of the soil beneath the working depth (120-220 mm) before the tillage operation varied from 36.91 to 37.62%, 37.80 to 39.31%, and 40.40 to 41.09% at test sites 1, 2, and 3, respectively. Further, the results of DMR tests indicate that the differences in the porosity of soil beneath the working depth before the tillage operation under most of the tillage treatments were statistically non-significant ($p \leq 0.05$) for the three sites.

The data were analyzed in terms of decrements in the soil porosity beneath the tillage depth under different treatments and the results are presented in Table 8 and plotted in Fig. 4(c). Table 8 shows that at test site 1 the highest decrement in soil porosity beneath the working depth was observed in T1 (6.61 ± 0.16%) followed by T4 (4.04 ± 0.36%), T3 (2.94 ± 0.50%), and T2 (2.25 ± 0.20%) with respect to the porosity of the soil before operation. Identical results were also observed at test sites 2 and 3 with average decrement in porosity of 6.50 ± 0.14%, 2.09 ± 0.16%, 2.82 ± 0.23%, and 3.7 ± 0.08% at test site 2; and 5.67 ± 0.14%, 2.06 ± 0.32%, 2.74 ± 0.19%, and 3.37 ± 0.14% at test site 3 under T1, T2, T3, and T4, respectively.

DMR tests indicate that the effect of different tillage treatments on soil porosity beneath the tillage depth were statistically significant 5% level of significance for the three test sites. The decrement in soil porosity indicates the possibility of freshly induced soil compaction beneath the tilled layer. The trend of higher or lower soil compaction in terms of soil porosity under different tillage treatments is similar to that of BD. Many studies conducted on the impact of the tillage traffic compaction on the porosity and structure of various soils have found a strong relationship between soil porosity and penetration resistance (Pagliai & De Nobili, 1993; Marsili et al., 1998). Tarawally et al. (2004) stated that compacted soil can destroy the soil structure, reduce porosity, limit air and water infiltration, and increases soil BD and CI. Many researchers (Green et al., 2003; Bhattacharyya et al., 2006) reported higher porosity values with conventional tillage as compared to no-till practice under tilled conditions. This may be due to the loose-soft, and fluffy structure of the tilled layer. However, Pagliai & De Nobili (1993) found lower porosity under tilled soil conditions.

Conclusions

This study quantifies the data regarding freshly induced soil compaction beneath the tillage working depth purely due to the tilling action of the active machinery such as rotavator, power harrow, and PTO-operated disc tiller in sandy loam soil. We provide proof that the active tillage rotary machinery causes soil compaction beneath the tillage depths due to the applied compressive force on the soil during their tilling action. The compacted soil was found to have a reduced porosity and increased BD and CI, which could destroy the soil structure and limit water infiltration. The results of the compaction study showed that the maximum soil compaction beneath the working depth in terms of increment in soil CI, increment in soil BD, and decrement in soil porosity occur with rotavator followed by the conventional tillage practice (one pass of cultivator and two passes of disc harrow), PTO-operated disc tiller, and power harrow at three different test sites. Undoubtedly, rotavators produce fine soil tilth at top soil layers, however, the high-speed rotating action of its blades compact the soil beneath its operational depth. Therefore, care should be taken regarding the selection of the optimum rotational speed of blades and forward speed of the tractor during tillage, as it directly affects the impact force exerted by the blades on the soil while traveling horizontally at the bottom of their stroke.

The crop residue management machinery such as Super Seeder equipped with 'LJF' type blades for wheat sowing and seed bed preparation in puddled soil for rice growing areas could be considered for future compaction studies.

Authors' contributions

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