

संरक्षण कृषि प्रथाओं के तहत मृदा कार्बन खनिज पर सरंधता और छिद्र आकार वितरण का प्रभाव

Effect of porosity and pore size distribution on soil carbon mineralization under conservation agricultural practices

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Effect of porosity and pore size distribution on soil carbon mineralization under conservation agricultural practices

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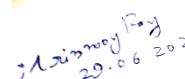
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This is to certify that the thesis entitled, “**Effect of porosity and pore size distribution on soil carbon mineralization under conservation agricultural practices**” submitted to the **Faculty of the Post-Graduate School, ICAR-Indian Agricultural Research Institute, New Delhi**, in partial fulfillment of the requirements for the award of **MASTER OF SCIENCE (AG.) IN AGRICULTURAL PHYSICS**, embodies the results of *bona fide* research work carried out by **Mr. Tridiv Ghosh, Roll No: 21086**, under my guidance and supervision and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help availed during the course of investigation as well as source of information have been duly acknowledged by her.

Place: New Delhi

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DEDICATED TO:

My dear Parents and Late Grandparents

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1. INTRODUCTION

Conventional tillage practices often lead to reduced infiltration, faster decomposition of soil organic matter (SOM) and poor soil structure *etc.* Continuous tillage of land season after season has led to development of subsurface hard pan and deterioration of soil structure because of loss of soil organic matter. Aggressive seed bed preparation through extensive tillage operations deteriorates the soil health at a very faster rate. To overcome these issues, the challenge for the scientist is to develop advanced soil conservation practices for higher productivity (Bhattacharya *et al.*, 2015) and improved soil health.

Conservation Agriculture (CA) is such an innovative resource-saving agricultural production system that aims to accomplish production intensification and high yields while enhancing the natural resource base and improving soil health. CA is characterized by four key principles, *viz.*, minimum soil disturbance, permanent or semi-permanent organic soil cover, diversification of crops grown in sequences and/or associations and controlled traffic. CA has changed most of the pattern of farming practices through modern mechanized agricultural operations. CA is a way of managing agro-ecosystems for sustained and improved productivity, better profits and also achieving food security while safeguarding the environment and improving the natural resources as well as soil health and agricultural sustainability. Different soil health indicators are improved aggregate stability, hydraulic conductivity, bulk density, field capacity moisture content, wilting point, available water capacity, OC, available N, P and K, microbial biomass and activity.

Several studies reported that most of the works on CA collect information on crop yields and carbon sequestration (Ghaley *et al.*, 2018) whereas, other soil health indicators are less emphasized. Hence in recent years, several researchers revealed that CA plus cover cropping possibly will increase organic carbon in soil, which leads to better soil physical structure (Tisdall and Oades, 1982), accelerates biological activity (Varvel *et al.*, 2006), better porosity and pore size distribution (Bhattacharyya *et al.*, 2006) and amplifies the C pool and nutrient cycling (Campbell *et al.*, 1996). So far, research on porosity and pore size distribution under CA management practices and their comparison with CT are

scanty. Hence, there is a need for more field-based studies in different parts of the world to provide additional proof of benefits of CA adoption.

Soil pores and pore size distribution (PSD) which impacts SOM turnover in the soil have not been studied directly due to paucity of information on 3D structure of the soil pore network. The spatial distribution of soil organisms depends on the availability and accessibility of the substrate in soil, water flows (Foster 1988), and porosity and pore size distribution (Bouckeaert *et al.*, 2013). PSD regulates the soil biological activities in two ways. Firstly, microorganisms can reside in pores having a diameter thrice than their body diameter (Kilbertus 1980 and Foster 1988) and secondly, PSD controls gaseous exchange and water allocation in the soil matrix. As PSD has great influence on soil microbial processes and community composition, PSD significantly regulates SOM content in soil.

The heterogeneous character of the soil structure determines the spatial variation of the soil hydrophysical properties. Due to its non-destructive and non-invasive character, combined with the possibility of providing detailed spatial information about the macropore networks, X-ray computed tomography can reveal clues to the mechanisms and the fate of SOM in soil, without altering the process. These techniques can bring an important contribution to the characterization of spatial variability of root systems, as well as rhizosphere processes. Soil pore structure plays a key role in the movement of water in both topsoil and subsoil, which is closely related to soil surface runoff and permeability, Moreover soil pore morphology affects the transmission and preservation of soil moisture. Rapid decomposition rates of added plant material were found in soils with a relatively high volume of pores with neck diameters 15–60 mm, whereas slow decomposition rates were found in soils with relatively high volume of pores with neck diameters <4 mm and 60–300 mm. Thomsen *et al.* (1999) found water to be the main factor controlling soil organic C (SOC) turnover and concluded that the effect of texture on SOM turnover is indirect; it is the soil structure determining the soil PSD that regulates water retention and, thus, also the water availability to the decomposer organisms.

All of these studies show the crucial role of the pore network and water distribution in C dynamics, but detailed knowledge about their interdependence is

lacking. The main reason for this knowledge gap is the lack of data on the 3D structure of the pore network, including spatial organization and information about its morphology in relation to C dynamics (Young *et al.*, 2001). In soils, irregularly shaped pores usually retain moisture better than circular pores, but the latter can transport water more efficiently. In other words, high soil pore circularity is beneficial for the transport and conservation of water in the soil, which can enhance water utilization and ensure that plants uptake sufficient water. X-ray computed tomography scanning is increasingly used as a non-destructive imaging technique for the high-resolution (mm- to μm -scale) characterization and quantification of soil physical properties. X-ray computed tomography scanning has been applied to the study of soil pore properties and pore distribution. This technique has also been introduced to accurately measure the number, size, and location of macropores (>1 mm in diameter). X-ray computed tomography scanning has been successfully applied in measurements of the distribution, number, shape and connectivity of macropores in longitudinal and transverse cross-sections of both undisturbed and packed soil column. The quantification of pore structure at mm to μm scales has been shown to be important in predicting micro-scale fluid flow properties. Hassink (1992) also found a good correlation between the habitable pore size fraction and N mineralization.

Carbon mineralization is greatly influenced by pore size; as the relative number of large pores is usually higher in sandy soils than in loamy and clay soils (Papendick and Campbell, 1981). In India quantification of porosity and pore size distribution in soil using 3D X-ray computed tomography has hardly been done. X-ray Computed microtomography allows for the visualization of pore structure at micron scale, but quantitative information on contribution of pores to the fate, protection and mineralization of soil carbon is still lacking. Hence, an attempt has been made in this study to evaluate the effects of soil management practices on pore structure and distribution and subsequently the carbon mineralization in soil.

Therefore, the current study has been proposed with the following objectives:

- To quantify porosity and pore size distribution under conservation agricultural practices in maize -wheat rotation
- To study the effect of pore size distribution on carbon mineralization in soil

Hypothesis of the study:

Conservation agriculture improves soil porosity and pore size distribution and carbon mineralization is affected by porosity and pore size distribution of soil.

2. REVIEW OF LITERATURE

The intensive tillage and other management practices in agricultural crop production systems can increase soil erosion, decrease soil health and water quality, and the ability to attain sustainable agricultural production systems. Soil erosion is constantly associated with tillage intensity, particularly during the spring season when soils are most susceptible to water erosion due to absence of vegetation or residue cover to shield the soil surface from high rain intensity. Soils under present production agriculture have lost major quantity of their carbon pool because of erosion, disintegration, and leaching. This loss in soil organic matter by cultivation is in part caused by the oxidation of organic matter and CO₂ discharge in addition to losses through surface runoff and soil erosion. Soil management and maintenance practices that protect soil health are not only economically and environmentally essential, but the correct methodology to endure and increase soil resiliency. Agricultural escalation is placing tremendous burden on the soil's capacity to sustain its functions leading to large-scale ecosystem degradation and loss of output in the long term. Consequently, there is a serious requirement to find early indicators of soil health degradation in reaction to agricultural management (Cardoso *et al.*, 2013, Indoria *et al.*, 2017).

For sustainable crop production and rational use of natural resources, it is essential to maintain of the soil physical health at its optimum level without hampering their quality. Presently the conventional tillage practices for crop production with intensive ploughing and removal of crop residue from the field increase soil compaction, surface crusting, soil erosion, decrease in water infiltration, and ultimately lead to overall soil physical health deterioration. So, to overcome these adverse effects of conventional tillage practices on soil physical health many agricultural scientists across the world have recommended conservation agriculture as a solution. Food and Agricultural Organization of the United Nations define conservation agriculture (CA) as "CA is a concept for resource-saving agricultural crop production technology that aims to achieve acceptable profits together with high as well as sustained production levels while simultaneously conserving the environment" (FAO, 2007).

Conservation agriculture is mainly based on four crop management practices-

- Minimum soil disturbance or no-tillage
- Permanent or semi-permanent retention of crop residue
- Crop diversification
- Control traffic

Minimum soil disturbance or no-tillage:

This principle of CA leads to improvements in soil structure, less soil erosion, an increase in organic matter content, cropping intensities, and crop yield. Kassam and Friedrich (2009) reviewed that CA practices improve soil biological activity through minimum tillage along with residue retention, which helps to form more stable aggregates with the adequate percentage of various sizes of pores, permitting better water infiltration and air movement.

Permanent or semi-permanent retention of crop residue:

Crop residue as a protective cover over the soil surface helps to suppress weeds, protects the soil from extreme weather patterns, helps to preserve soil moisture, and avoids compaction of the soil. Ghosh et al. (2015) reported that a permanent soil cover is essential to protect the soil from the harmful impact of rainfall and sunshine and helps to enhance the microbial population in the soil with a continuous supply of “food”; and modify the microclimate of the soil which gives ideal condition for growth and improvement of soil organisms, including plant roots. This improves soil aggregation, soil biological activity, and biodiversity, and carbon sequestration.

Crop diversification

Generally, cereal-cereal monocropping like rice-wheat and maize-wheat are followed on large areas adversely affecting the soil health. Rotation of crops is not only essential to offer a diverse “diet” to the soil microorganisms, but also for exploring nutrients from different soil layers that have been leached to deeper layers that can be “recycled” through crop rotation. Furthermore, crop diversification leads to an enhancement of soil flora and fauna diversity. Cropping sequence and rotations involving legumes help in minimizing

pest instance, through disruption of the life cycle, biological nitrogen fixation, control of off-site pollution, and enhancing biodiversity. (Dumanski *et al.*, 2006)

Control traffic:

Controlled traffic farming restricts traffic in the field to the fixed tracks. While these tracks are heavily compacted, without any compaction of the root zone leading to better soil structure and higher yields. The better growth of plants adjacent to the track due to border effect can easily compensate for the area which is lost in the traffic zones and the overall yields are usually higher compared to conventional systems with random traffic (Kerr, 2001). Zero tillage systems-controlled soil compaction due to machine traffic in the cropping zone is completely avoided. Other benefits are fuel savings as tires run on compacted tracks so the traction is more efficient (RWC-CIMMYT, 2003).

2.1. Impact of conservation agriculture on soil physical properties

It has already been discussed that CA makes desirable changes in many soil physical properties, *viz.* increase in soil water infiltration, reduction in water runoff and soil loss, and decrease in evaporation loss, just after its inception, while other desirable changes such as improvement in soil structure, porosity, macro-micro fauna activity, and organic matter content, occur over a long-term basis.

2.1.1. Bulk density and total porosity under CA

Bulk density is one of the most important soil physical parameters which determines soil compactness. The bulk density greatly depends on inherent soil qualities as well as on management practices. Gantzer & Blake (1978) reported that zero tillage (ZT) has higher bulk density as compared to conventional tillage. Bautista *et al.*(1996) found that zero-tillage with residue retention reduced bulk density (BD) significantly in a semi-arid ecosystem. Several researchers (Ehlers, 1983; Pikul *et al.*, 1990; Sauer *et al.*, 1990) have found that, on certain soils, switching from a till to a no-tillage cropping system caused an increase in bulk density and decrease in porosity in the no-till system. Mielke *et al.* (1986) have done a study comparing bulk density between no-till systems and moldboard plow systems by taking seven soils at two depths (14 combinations), They have reported

in six instances of greater bulk density for the no-till system, one instance of greater bulk density for the moldboard plow system, and no bulk density differences between these systems in seven instances.. Another study Horne et al. (1992) have shown that lower bulk density at a depth of 3–7 cm in zero tillage than in conventional tillage, with no significant changes in the deeper layer. The long-term retention of crop residue helps to decrease bulk density and increase effectiveness. The effect of additional mulch left on the surface for reducing bulk density is very clear in the 0–3 cm and to a lesser range in the 3–10 cm soil depth. (Blanco- Canqui and Lal, 2007).

The physical consolidation of soil particles against an applied force is called soil compaction. The soil compaction results in a reduction in porosity, restriction of air and water movement, and depletion of soil structure. The reason behind compaction in agriculture is the heavy use of farm machinery and the applied pressure of wheels. The tillage practices under inappropriate moisture lead to an increase in compaction. The use of the same cropping sequence and equipment year after year in conventional tillage causes the formation of subsoil compaction. Different crop rotations and residue retentions and crops with different rooting depths used in CA practices have proved to reduce the compaction constraints.

However, Logsdon & Karlen (2004) reported that farmers need not to worry about an increase in compaction as BD is not a useful indicator while shifting from CT to NT on deep loess soils in USA. Fabrizzi et al. (2005) also showed higher penetration resistance and BD in NT experiments in Argentina, but the values were below the thresholds to affect crop growth.

2.1.2. Hydraulic conductivity and infiltration under CA

The conduction of water within a soil profile against the hydraulic gradient is termed as Hydraulic Conductivity. The hydraulic conductivity of soil is affected by various factors such as parent material, topography, and climate, *etc.* One of the important roles is played by the tillage practices is to affects soil bulk density and porosity. Obi and Nnabude (1988) and Celik (2011) showed that the tillage practices either had no major change or a negative impact on hydraulic conductivity. McGarry et al. (2000) showed that zero tillage practices improved the hydraulic conductivity of soils. The probable reason for the increased hydraulic conductivity of no-tilled soils was improved pore size distribution, pore

diameters, pore continuity and an increase in numbers of macropore (Cameira *et al.*, 2003). Logsdon *et al.* (1995) showed that the increase in hydraulic conductivity was due to the greater activity of fungi and buildup of organic matter due to the deposits applied in the field. Soil infiltration is another soil physical property affected by CA practices and it is defined as the downward entry of water from the soil surface. The infiltration characteristic of the soil is important for defining the results of different tillage, conservation and irrigation practices of a particular region (Sumathi and Padmakumari, 2000). Saturated hydraulic conductivity was significantly higher under reduced tillage (RT) compared to No-tillage (NT) whereas for conventional tillage (CT) they ranged in between as reported by Kreiselmeier *et al.* (2020).

Lal (2008) showed that residue cover enhances the interception of the rainfall, reduces the soil crusting and soil losses due to runoff, and therefore it helps to increase the soil water infiltration rate. The decomposition of residue helps in improving soil structure through enhanced soil aggregate stability and soil porosity, which also improves the soil water infiltration rate (Jordán *et al.*, 2010) Sharratt *et al.* (2006) explained that the presence of mulch may restrict water infiltration by imparting water repellent and hydrophobic properties to the soil surface.

2.1.3 Aggregate stability under CA

Aggregate stability and size information is a useful property to predict or evaluate the effect of different agricultural technique like tillage practices, the addition of organic matter or to acquire knowledge about the susceptibility of soil to wind and water erosion (Nimmo *et al.*, 2002). Fuentes *et al.* (2012) showed that zero tillage in combination with crop diversification and crop residues retention resulted in a higher proportion of stable macro-aggregates (40%) and higher mean weight diameter (MWD). Paul *et al.* (2013) reported that CT negatively related to soil aggregate stability when compared to reduced tillage, as indicated by lower values of MWD upon wet sieving at 0–15 cm depth. This suggests an increased susceptibility to slaking and soil erosion. Bhattacharyya *et al.* (2013) also reported that after 4 years ZT with raised bed plots had a greater proportion of large macroaggregates (2–8 mm) than CT with a flat and CT with raised bed plots. Oicha *et al.* (2010) showed that the aggregate stability of permanent bed (PB) (0.94) was higher than CT (0.83) but the difference was not significant.

2.1.4 Soil carbon, different pools of SOC and carbon stock under CA

The most important soil quality indicator is the soil organic carbon (SOC) especially the concentration of SOC at the surface soil. “The soil organic carbon plays a great role in nutrients holding, reducing soil erosion, and improving water infiltration. The distribution of SOC in the profile is affected by tillage practices and SOC content. The SOC content in the surface layer is higher in the case of zero tillage compared to conventional tillage (Chakrabarti *et al.*, 2014), whereas a higher SOC content is found in the deeper layers of tilled plots with residue incorporation. Crop residues are precursors of the SOC pool, and retention of more crop residues to the soil is associated with an increase in SOC concentration (Bhattacharyya *et al.*, 2012). “The rate of decomposition of crop residues depends not only on the amount retained but also on soil characteristics and the composition of the residues. Bhattacharyya *et al.* (2013) showed that plots under CA had around 33% more labile SOC (Pool II) than CT plots (2.01 g C kg^{-1}) in the 0- to the 5-cm soil layer. Dou *et al.* (2008) observed that CA significantly ($P < 0.05$) improved SOC content and they compared the proportion of all labile SOC pools with CT, particularly for 0-15 cm soil layer, after 20 year of CA adoption in south-central Texas. They found significantly higher labile SOC pool in CA and that was possibly owing to greater biomass carbon. Andruschkewitsch *et al.* (2013) reported that in case of CT, the residue from the harvest is more uniformly distributed up to 30 cm soil depth while on NT and RT there is a surface layer accumulation.

Madari *et al.* (2005) in has experimented in Brazil and reported that NT with residue cover enhances the aggregate stability and there was an increment of aggregate associated total organic carbon compared to CT. Roldan *et al.* (2003) also showed that after the cultivation of maize under 5 years NT condition has significantly increased wet aggregate stability over CT and they have also reported the enrichment of soil organic carbon (SOC), microbial biomass and soil enzymes.

2.2. Effect of CA and CT on porosity and pore size distribution

There are different sizes and shaped pores are present in the soil, and their characteristics influence greatly on the physical, chemical, and biological behavior of the soil. The pores of different dimensions are developed due to different abiotic (e.g. traffic and tillage, wetting and drying, freezing and thawing, *etc.*) and biotic (e.g. burrowing of macro and

micro fauna, root growth) factors (Kay and Vanden Bygaart, 2002). The alteration of pore characteristics in the Spatio-temporal scale can be done by following different tillage practices. The changes of pore characteristics are mainly dependent on the magnitude, frequency, and form of stresses that have been imposed on the soil, applications of crop residue, and the population of microorganisms.

Different agricultural management practices affect pore-size distribution, pore connectivity, and tortuosity. Tillage by heavy machinery reduces the macroporosity, disrupts pore continuity, and affects bio pore formation (Boersma and Kooistra., 1994). Piccoli et al. (2017) reported that CA practices influenced the ultramicroporosity class (0.1–5 μm) ($1.86\text{E-}01$ vs $1.67\text{E-}01 \mu\text{m}^3 \mu\text{m}^{-3}$) which is linked to SOC content of the soil. Vanden Bygaart et al. (1999) showed that ZT practices decreased the number of 30- to 100- μm pores with a resultant increase in 100- to 500- μm diameter pores within 4 year of ZT practice.

The development of desirable soil structure is important for getting good physical characteristics, which make agriculturally sustainable. Pires et al. (2019) employed X-ray computed tomography to evaluate the effect of three different tillage systems (i.e. zero-tillage, ZT; reduced tillage, RT; conventional tillage, CT) on the soil porous system of an Oxisol. They have used 0-10 cm depth undisturbed soil core for scanning through X-ray computed tomography. The results have been shown that the soil under ZT (without crop residue) has the smallest porosity in comparison to the other management practices. The largest porosity and the most connected pores have been seen in conventionally tilled soil.

2.3. Use of X-ray computed tomography in soil

The X-ray computed tomography is a modern tool for structural analysis of different materials. In the present scenario, it gives an opportunity in the soil science for gaining valuable information of the soil. The quantification of the internal soil structure is an important key for understanding different physico-chemical and biological processes occurring in the soil (Calistru *et al.*, 2015). In the last decades, X-ray computed tomography has provided a non-destructive means to observe and quantify soils in 3D. It is mainly used in determining the spatial distribution of soil pores (Young *et al.*, 2001, Nunan *et al.*, 2006), pore network (Al-Raoush and Willson, 2005), bulk density,

permeability (Ketcham and Carlson, 2001, root architecture (Mooney, 2012), etc. Recently X-ray computed tomography gives a new way to study soil pore structure. X-ray computed tomography data represented as grayscale images and the proper selection of segmentation methods to binarized it has a great influence on the soil structure characterization. Torre et al. (2017) used X-ray computed tomography for the visualization of soil structure under different tillage treatments namely chisel plough, moldboard plough, and roller. By comparing X-ray computed tomography data for all 3 treatments they have concluded that moldboard creates a higher complexity in soil structure as it removes the soil from the surface. Chisel disrupts the soil aggregates and finally, roller is an intermediate case where, the soil is moderately disturbed. Grayling et al. (2018) used X-ray computed tomography for tracing the movement of a particle in the soil for that they have selected decabromodiphenyl ether (DBDE) as a proxy material of solute. For mapping, the 3D pore geometry and visualization of the concentration distribution proxy material through a soil column X-ray computed tomography was used. They have applied proxy material and subsequently leached through the soil over 5 hours to trace the spatial and temporal movement of the particle. For the comparison with the imaged data, the soil elute was collected from the bottom of each column and the proxy material concentration measured using gas chromatography simultaneously. The results showed that the tracer material initially moved rapidly through the upper portion of the soil but subsequently became immobile, despite repeated elution with water as confirmed by imagery.

Soil liming is efficient for the reclamation of acidic soils in the agricultural field but little research has been done to understand its effect on soil structure in the microscale. Ferreira et al. (2018) used X-ray computed tomography to get valuable information about the soil micromorphological characteristics under the application of lime. They have shown that there was an improvement of the soil chemical attributes only at layer A by applying liming where it also made positive effects on the soil porous system within thirty months.

The flow of water in the soil highly depends on soil physical properties like texture, structure, pore characteristics, etc. The hydraulic conductivity of unsaturated peat soil is controlled by the air-filled porosity, pore size, and geometric distribution as well as other

physical properties of peat materials. Rezanezhad et al. (2009) conducted a study to examine how the flow of water through peat soil is affected by the size and shape of the pore. They used X-ray computed tomography (at 45 μ m resolution to detect pore size and their configuration under changing water regimes. The study suggests that hydraulic conductivity of peat soils is greatly controlled by a pore shape coefficient, which is usually assumed to include properties such as pore size distribution, path tortuosity, the roundness and sphericity of the pores.

2.4. X-ray computed tomography and soil porosity and pore size distribution

The pore structure and their distribution in the soil exerts a sound influence on the distribution of micro-organisms, moisture, and air. Therefore, it's having a potential role in controlling soil organic matter decomposition. Sleutel et al. (2011) tried to investigate the relation between the pore network, microbial habitat, and organic matter decomposition. Yang et al. (2018) used different soil amendments like straw mulch, superabsorbent polymer (SAP), and organic fertilizers for improving soil structure and porosity. They have used X-ray computed tomography to determine the number, size, location, and morphology of pores. They have found out that combined application of amendments improves soil pore structure more effectively as compared to individual applications. They have also reported that the application of both straw mulch and organic manure improves soil porosity and soil structure more effectively as compared to other combinations. The development of desirable soil structure is important for getting good physical characteristics, which make agriculturally sustainable. Pires et al. (2019) employed X-ray computed tomography to evaluate the effect of three different tillage systems (ZT; RT and CT) in the soil porous system of an Oxisol. They have used 0-10 cm depth undisturbed soil core for scanning through X-ray computed tomography. The results showed that the soil under ZT has the smallest porosity in comparison to the other management practices. The largest porosity and the most connected pores have been seen in conventionally tilled soil.

The soil macropores as a preferential pathway for the movement of water, air, and chemical in different soils has long been recognized. However, the quantitative information of macropore and their relationships with different soil types and land use

remains lacking. Lou et al. (2010) have taken up a study to quantify 3D macropore network using X-ray computed tomography and to investigate the influence of soil type and land use on soil macropore. After the analysis, they found that soil type and land use and their interaction significantly influenced soil macroporosity, surface area, network density, node density and length density, mean tortuosity, and hydraulic radius. The study indicated improved quantitative evaluation of soil macropore that significantly impacted the prediction of non-equilibrium flow and modeling of chemical transport in the field soil. Delerue et al. (2003) used X-ray computed tomography for calculating the equivalent hydraulic conductivity. They developed a pore network utilizing 3D soil images by integrating pore size and connectivity parameters.

Elliot and Heck (2007) compared the optical and the X-ray computed tomography method for the determination of void space. They have selected an identical region for both types of the image of a small soil section for the comparison. They reported that the optical method was efficient in continuous and linear void identification whereas X-ray computed tomography identified more number of voids with higher circularity. Rogasik et al. (2003) analyzed macropore size, length, and connectivity of pores under different agricultural practices at the spatial scale of $0.25 \times 0.25 \times 1$ mm. Sander et al. (2008) utilized X-ray computed tomography for the visualization of the size and structural pore connectivity, aggregate arrangement and also determined the vertical bulk density distribution in the upper soil horizons under paddy fields.

Kim et al. (2010) studied how 3D pore geometry is affected by soil compaction using X-ray computed tomography. They have used a moderate compaction treatment used for this study to reduce the number of pores and porosity within the upper 10 cm of the soil. The results they have shown that soil saturated hydraulic conductivity was also significantly reduced by compaction. A study was carried out by Beraldo et al. (2014) for the quantification of soil porosity using X-ray computed tomography under conventional tillage, no-tillage, and native forest. They have shown that there was a change in soil porosity under different management practices, and the difference was more significant in conventional and no-tillage compared to the area under forest.

Hamamoto et al. (2016) used X-ray computed tomography for obtaining information regarding pore network under different compaction levels for the column of sand and glass beads which represents different shapes and sizes of particles. They have also measured the mass transport parameters like gas diffusion coefficient, air permeability, and saturated hydraulic conductivity. The results showed that the round sand and glass beads had larger pores, higher pore coordination number and lower volumetric surface area compared to angular sands and glass beads which resulted in higher value saturated hydraulic conductivity, gas diffusion coefficient and air permeability under the dry condition.

Dal Ferro et al. (2013) showed that with an increase in SOC the pores of $>560\ \mu\text{m}$ in the soil cores increased and, at the same time, there was a decrement of $80\text{--}320\ \mu\text{m}$ pores. However, aggregate porosity, $12.5\text{--}200\ \mu\text{m}$ pore size was minimally affected by the SOC and management practices. Pituello et al. (2016) reported that residues decreased mesoporosity ($30\text{--}75\text{mm}$), while their effect on macropores ($>75\text{mm}$) was in terms of shape, increasing the elongated pores rather than their size-frequency. Borges et al. (2019) showed that the soil under NT had the lowest values of macroporosity and saturated hydraulic conductivity, which may be due to the possible compaction by agricultural traffic. However, the water retention analysis showed that there was a greater volume fraction of mesopores and micropores under NT than under CT.

2.5. Pore size distribution and Carbon Mineralization

The use of heavy machinery in agricultural activities increases the soil compaction, which leads to greater soil bulk density and micro porosity, reduction in hydraulic conductivity, and O_2 and CO_2 diffusion rates. Thus, soil compaction has a major influence on soil microbial activity and the processes related to organic matter decomposition and nutrient cycling. A study was carried out by Silva et al. (2011) under controlled conditions to evaluate how the microbial activity and soil carbon (C) and nitrogen (N) mineralization affected by soil compaction. They reported that soil compaction had a significant influence in nitrogen mineralization and TOC. They have also reported the reduction in TOC turnover with an increase in soil compaction was due to increased physical protection of the soil organic matter and lower aerobic microbial activity.

There is a little knowledge about the factors that regulate the carbon mineralization at the different pore-scale or how these factors are influenced by the pore network in the soil. Ruamps et al. (2013) tried to understand how the decomposition of organic carbon varies with the pore network within the soil and they have also tried to find out the relative importance of local environmental properties relative to biological properties as controlling factors. The results have shown that microbial metabolism does not play a significant role in determining the rate of decomposition of soil organic carbon but the substrate availability is the key. Many scientists have reported that the application of different soil amendments improved soil physical and biological properties. Yazdanpanah (2016) used urban municipal soil waste (MSW) compost and alfalfa residue as an amendment in two different texture soils namely clay loam and loamy sand. The results they have shown that there was an improvement of soil aggregate stability and enhancement of soil porosity especially macroporosity due to the application of amendments. Moreover, in case of microbial respiration i.e. CO₂ emission, the application of MSW resulted in higher values of microbial respiration in the clay loam soil than in the loamy sand soil, whereas the reverse was found by Killham et al. (1993) who introduced ¹⁴C labeled glucose in two different size pore classes of a vertisol and they have tried to compare the ¹⁴C flow in two different matric suction. After the 4-week incubation study, they reported that glucose turnover was greater when the substrate was located in larger pores and the soil was subjected to low water potential. So, the difference in the rate of carbon turnover indicates the compartmentalization of substrate and microbial habitat in different size pore space in the soil.

2.6. X-ray computed tomography, pore size distribution and carbon mineralization

Bouckaert et al. (2013) used-ray computed tomography for the quantification and distribution of pore in a unit pore volume and they tried to develop the relationship between pore volume and soil carbon mineralization. They have established the correlation between the volume of each pore neck classes and slow pool carbon mineralization rate and found out that pore neck size of 150-250, 250-350 and >350 µm

having positive correlation (r) = 0.572, 0.598 and 0.516, respectively because larger pores enhances aeration whereas $<9.44 \mu\text{m}$ pore neck classes having negative correlation due to obstruction of microbial activity and mobility of enzymes.

Quigley et al. (2018) used X-ray computed tomography to understand how different size pores affect the spatial distribution of newly added carbon immediately after plant termination and 1 month after incubation. They have found out that soil with a pore size of 40-90 μm associated with quick decomposition of newly added carbon and pore size with $<40 \mu\text{m}$ associated with carbon protection.

Physical protection of soil organic carbon is an important component of carbon storage in the soil, but the mechanisms are still not clear. A study was carried out by Negassa et al. (2015) to understand the influence of soil structure and the spatial distribution of soil pores on plant residue decomposition, CO_2 emission from the soil and the structure of soil bacterial communities, with or without the presence of plant residue. They showed that larger pore ($>30 \mu\text{m}$) and highly connected pores ($>6.5\mu\text{m}$) are associated with a higher amount of plant residue decomposition. In both large and small pores are dominated with copiotrophic organisms, associated with cellulose decomposition. But the number of oligotrophic *Acidobacteria* groups are found more abundant in small size pores.

3. MATERIALS AND METHODS

3.1. Study Area

The experiment was conducted in maize-wheat cropping system on the maize crop during *Kharif* 2019, at the Agricultural Research Farm (MB-14B), Indian Agricultural Research Institute (IARI), New Delhi.

3.2. Climate and soils:

The study area falls under semi-arid climatic conditions, prevalent with dry hot summer and cold winter season. The mean annual precipitation is 710 mm and 80% of the total rainfall occurs from July to September months due to south-west monsoon and the rest rainfall occurs from December to February months due to Western disturbance (Das *et al.*, 2018).

The soil up to 15 cm soil depth of the experimental field having sandy clay loam texture with pH 7.7, Electrical Conductivity (EC) of 0.64 dSm⁻¹, Walkley & Black C (oxidizable SOC) 5.2 g kg⁻¹, KMnO₄ oxidizable N 182.3 kg ha⁻¹, 0.5 M NaHCO₃ extractable P 23.3 kg ha⁻¹ and 1 N NH₄OAc extractable K 250.5 kg ha⁻¹. The soil contained sufficient amounts of CaCl₂ extractable S and DTPA extractable micronutrients as all of these were above the critical deficiency limits reported by Das *et al.* (2018)

3.3. Experimental details:

The experimental treatments consisted of conventional tillage (CT), permanent narrow bed (PNB) (one row of Maize per 40 cm wide bed and 30 cm wide-furrow, Figure 3.1), permanent broad bed (PBB) (two rows of maize per 110 cm wide bed and 30 cm wide-furrow, Figure 3.2), PBB along with crop residue (PBB+R), and PNB along with crop residue (PNB+R) since 2010. From 2012 onwards, another two treatments zero tillage (ZT) and ZT with residue retention of previous crops (ZT+R)) were added. There were 1.5 m wide gaps between the plots and each plot surrounded by embankments for irrigation purposes.

In CT plot there was one ploughing with tractor-drawn disk plow, cultivator, and harrow followed by levelling were done in every season for getting good tilth. In the case of ZT, PBB, PNB both with and without residue retention no ploughing was given.

In the residue retention plot, about 40% of wheat straw yield and maize stover was retained as residue. In 2009–10 wheat straw yield was nearly 6.5 t ha^{-1} . Therefore, 40% of 6.5 t ha^{-1} *i.e.* nearly 2.6 t ha^{-1} *ex-situ* wheat residue applied on the PBB+R and PNB+R plots in maize crops at the beginning of the experiment in first year (2010-11). The *in-situ* maize and wheat crop residue were kept in all the residue retention plots (*i.e.* ZT + R, PNB + R, PBB +R) which was available from the winter season (*i.e.* wheat crop) of first year onwards. For CT and residue removal plots, wheat and maize crops were manually harvested by cutting plants at around 3–4 cm above the soil surface. Therefore, it was estimated that about 4.5% of wheat straw was left as stubble in CT and other residue removal plots in all the years. In the case of residue retention plots, at 40 cm height from the base, the standing maize plants were cut manually and left in situ as anchored residue and estimated if 40% retention was not fulfilled than loose residue was uniformly applied in the residue retention plot. Similarly, wheat plants were harvested at 40 cm height from the base of plants for grains with a combined harvester, and rest was retained as stubble. The three years cumulative estimated amounts of residues returned to the maize-wheat system were 0.92, 0.86, 13.45, 0.90, 14.90, 1.20 and 10.90 Mg ha^{-1} in the plots under CT, PNB, PNB + R, PBB, PBB+ R, ZT, and ZT + R, respectively (Das *et al.*, 2018).

3.4. Sampling details:

For the analysis of all the parameters, the sample in two forms one is in the core for pore size distribution, bulk density, hydraulic conductivity, and mineralization study and another as loose sample for carbon and aggregate analysis. The samples are taken at two times, one at the time of sowing of maize and another one at the time of harvesting. The samples from 4 different depths of soil *viz*, 0-5 cm, 5-15 cm, 15-30 cm, and 30-45 cm, with 3 replications.

3.5. Soil physical properties studied

3.5.1. Porosity and pore size distribution:

Porosity and pore size distribution was measured by using X-ray Computed Tomography). The instrument has mainly 3 parts *viz*; X-ray source, sample holder, and detector (Figure 3.3). The fundamental principle of X-ray computed tomography is directing X-ray through the object at different orientation and the decrease in intensity is measured by the detector.

Sample preparation: The oven dried core samples were used for micro X-ray computed tomography scanning.

The steps involved in scanning have been described below:

For generating X-ray, a voltage of 120 kV and 90 μ Am current was applied. For scanning the soil sample voxel size (volumetric representation of a 2D pixel in 3D) of 58 μ m was used, the sample was rotated from -180° to $+180^\circ$ in front of X-ray source such that a total of 1000 projection images for each sample can be taken utilizing 500 ms exposure of the detector.

Determination of porosity of the soil sample through X-ray computed tomography involves three principal steps: (i) sample mounting; (ii) scanning; (iii) image processing and image analysis (Figure: 3.3) The soil sample was mounted separately to a sample holder in front of the X-ray source. Thereafter, samples were scanned individually with the help of an X-ray computed tomography system (Phoenix v|tome|x s, GE Sensing and Inspection Technologies GmbH, Wunstorf, Germany) for analyzing their porosity.

After the acquisition of corrected volumetric data from the system, image processing was done using VG Studio Max software (Version 2.2.3, Volume Graphics GmbH, Heidelberg, Germany). The 3D model of the sample is generated by selecting the threshold of the material and the background. After that porosity of the sample is determined by selecting the porosity module of the software. The pores (Table 1) were classified based on pore diameter and volume percentage, sphericity, compactness, and the number percentage of pores in each class that has been calculated.

The sphericity of the pore (sph_X-ray computed tomography) was calculated as the ratio of the surface area of a sphere (with the same volume -V- as the given particle) to the surface (S) area of the particle (Wadell, 1935):

$$\text{Sphericity} = \sqrt[3]{(36\pi V^2)/S}$$

The maximum value of sphericity will be 1, which would be for a perfect sphere. For a complex, non-spherical object the surface area of the volume-equivalent sphere will be much smaller than the particle surface area, thus sphericity will be low.

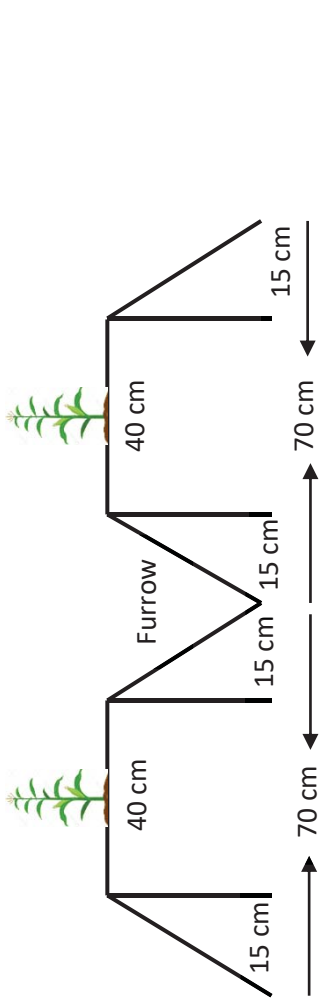


Figure 3.1: Schematic diagram of permanent narrow bed (PNB)

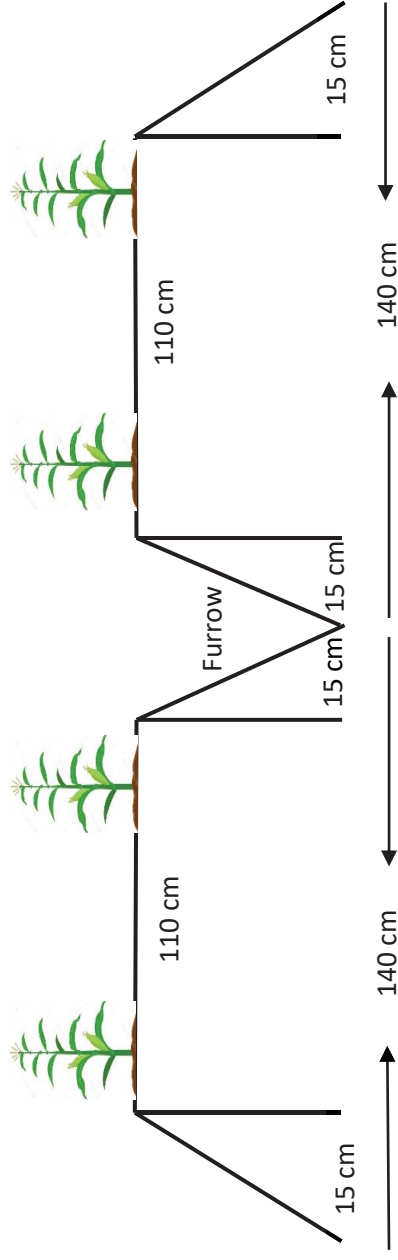


Figure 3.2: Schematic diagram of permanent broad bed (PBB)

Detector Soil sample Sample holder X-ray Source

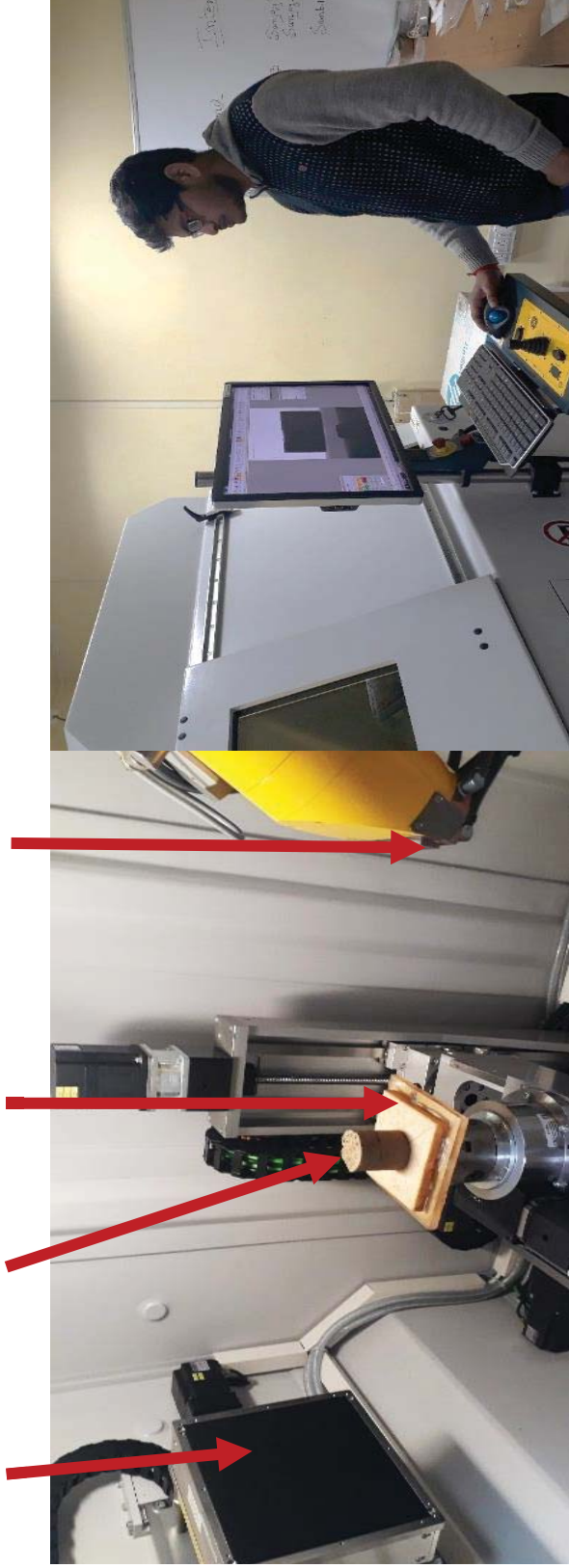


Figure 3.3: Components of X-ray computed tomography Scanner

3.5.2. Bulk Density (BD)

The soil bulk density was measured with by core auger method (Blake and Hartge,1986). The step followed for measurement are given below:

The main principle behind the core auger method is sampling a soil core from the desired depth, generally cylindrical core sampler is used then the oven-dry mass of soil sample per unit volume of the corer is calculated. The Core cutter made with a galvanized iron cylinder of 15cm height and 5.5cm diameter was used. A double cylinder drop hammer sampler, with a core is designed to take out a cylindrical core of soil. Inside the core cutter, the sectional cylinder with 6 cm height and 6cm diameter and with two rings of 6cm diameter and 2 cm height were placed. Then the core cutter is screwed with the collar of the sampler from the upper side. The collar is connected with a thick iron rod nearly 85 cm long. At the top of the rod, there is a Handel on both the side and a thick iron piece in the middle where the hammer is dropped. The inner cylinder which consists of an undisturbed soil sample was then taken out from desired depth and both the ends of the inner cylinder head were trimmed cleanly with a knife. After that, the core rings are cut from both the end of the cylinder, this cylinder which contains the soil sample yields a core, the volume of the core was calculated by measuring the diameter and length of the cylinder. The soil core was oven-dried at 105°C for 18 to 24 hours then the weight of core was taken. Bulk density was obtained by dividing the weight of the soil with the volume of the core.

BD was calculated by the following formula in equation 1:

$$BD(Mgm^{-3}) = ((X-Y))/V \dots\dots\dots (1)$$

Where, X=Weight of the core with oven-dry soil (g)

$$Y=Weight of core (g); V=Volume of core (cm^3) = 117.75cm^3$$

3.5.3. Aggregate analysis

The aggregate can be defined as a group of primary particles joined with each other more strongly than to other surrounding soil particles (Kemper and Rosenau, 1986). The amount of disruptive forces is required to disintegrate these aggregates, which is proportional to the force of attraction within aggregates. The aggregate analysis was

performed by using the Yoder wet sieving apparatus. At first 100 g air-dried soil sample was taken after passing through the 8mm sieve, then the soil sample was spread evenly on top of 2 mm sieve followed by a nest of three sieves are there with the opening of 2 mm, 0.25 mm, 0.053 mm. The sieve set was lowered into the water bath in such a way that the sample in the top sieve was just below the water level in the upstroke of the apparatus. The sieve set was moving ups and down approximately 30 times per 10 minutes in water as recommended by Yoder (1936). The sieves were taken out from the water, each sieve was washed several times separately and the residue is passed through a filter paper then the oven-dried weight was taken (Figure 3.4).

3.5.3. Mean weight diameter

Mean weight diameter of the aggregates was calculated using the formula (equation 2):

$$MWD = \sum xi wi \dots\dots\dots (2)$$

Where xi is the mean diameter of ith class (mm), wi is the weight of ith class



Figure 3.4: Aggregate analysis

3.5.4. Saturated Hydraulic Conductivity (Ks)

The constant head permeameter method (Klute and Dirksen, 1986) was used to measure the saturated hydraulic conductivity. A permeability cell that had a fixed height of 6cm and a diameter of 5 cm was used for conduction the experiment. A constant head of 1cm was maintained by a testing apparatus equipped with an adjustable constant head reservoir and an outlet reservoir. Before starting the measurements, the soil samples were saturated overnight. A cylindrical soil sample of cross-sectional area A and length L was placed between two porous plates that do not provide any extra hydraulic resistance to the flow.

A constant head difference, H_2-H_1 was applied across the test sample. By measuring the volume V of the test fluid that flows through the system during time t , the saturated hydraulic conductivity K_s of the soil was determined. The recordings were repeated until a fixed-rate value was obtained. Using these values, the saturated hydraulic conductivity was calculated by the Darcy Law (equation 3):

$$K_s = \frac{VL}{At(H_2-H_1)} \dots\dots\dots (3)$$

Where K_s is saturated hydraulic conductivity (cm/hr); A is an area of cross-section of the core (cm^2); t = time of water flow (hr); (H_2-H_1) is the hydraulic head difference at the top and bottom of top and bottom of the core; V =volume of water(ml) collected in the beaker below the bottom of the core during time t ; L = length of core(cm).



Figure 3.5: Constant head permeameter

3.5.5 Infiltration:

The Infiltration characteristics for conventional tillage (CT), permanent narrow bed (PNB), PNB with residue retention (PNB+R), permanent broad bed (PBB), PBB with residue retention (PBB+R) and Zero tillage (ZT) plot was determined by using Double Ring Infiltrometer, which consists of two concentric cylinders. At the time of measurement, the observation is made based on the inner cylinder having a diameter of 20 cm. In the outer cylinder (30 cm diameter) the same level of water was maintained as an inner cylinder which helps to minimize the seepage loss. The volume of water that has

been added up to a fixed point in the cylinder after the particular time interval is noted. The rate of infiltration is calculated by following this formula-

$$\text{Infiltration rate (cm/hr)} = \frac{\text{the volume of water added (cm}^3\text{)} \times 60}{\text{time (min)} \times \text{cross-sectional area of the inner cylinder (cm}^2\text{)}}$$

Many scientists proposed different models of infiltration *viz*; Green-Ampt model (1911), Kostiakov(1932), Horton(1938), Phillips(1957), Overton(1964), Smith and Parlange model(1978) and Singh and Yu(1990). The selection of the infiltration model depends on the types of soil and field conditions. Among the above-mentioned models Green-Ampt model (1911), Kostiakov (1932), Horton (1938), and Phillips (1957) are commonly used due to its simplicity and ease of computation, out of which Kostiakov, Horton is empirically derived and Phillips & Green-Ampt model is physical processed based.

Prediction models for infiltration rates:

A brief description of the infiltration models used in this study is as follows.

Empirical Models:

- 1. Kostiakov model:** Kostiakov (1932) proposed an equation to calculate cumulative infiltration

$$I = at^{-b}$$

$$i = at^{-(b+1)}$$

Where, I = Cumulative infiltration (cm)

i = Infiltration rate (cm hr⁻¹)

t = Time (hr)

a and **b** are constants with $a > 0$ and $0 < b < 1$.

The parameters in the Kostiakov model were determined by plotting the infiltration rate (i) versus time (t). The slope of the curve was **b** and the intercept on Y-axis was **a**.

Physical Process-based Model:

1. Green-Ampt Model

$$i = i_c + \frac{B}{I}$$

i = Infiltration rate of soil (cm hr⁻¹)

i_c = Steady state infiltration rate (cm hr⁻¹)

B = constant

2. Philip model: Philip (1957) proposed an infinite series solution of Richard's equation to drive a relationship between cumulative infiltration and soil properties represented as

$$I = St^{0.5} + Kt$$

$$i = \frac{1}{2}St^{-0.5} + K$$

Where,

I = Cumulative infiltration (cm).

i_o = Initial infiltration rate (cm hr⁻¹)

t = Time (hr)

S = Sorptivity of soil.

K = Saturated hydraulic conductivity (cm hr⁻¹).

The infiltration rate was plotted against reciprocal square root time. The slope of the best-fitted curve represented the value of K and the intercept gives the value of $S/2$.

The model performance was checked by computing the coefficient of determination (r^2), Root Mean Squared Error (RMSE), and Mean Absolute Error (MAE). The r^2 values describe the proportion of the total variance explained by the model. It varies between 0 (no correlation) and 1 (perfect correlation). The RMSE indicates the actual size of the

errors and MAE measures the errors between paired observations expressing the same phenomenon.

i. Mean Absolute Error (MAE)

MAE is the average absolute difference between predicted and the observed value of data. It is computed as

$$\text{MAE} = \frac{\sum_{i=1}^n |y_i - x_i|}{n}$$

where

x_i = Observed data values.

y_i = Estimated (computed) data values.

ii. Root Mean Square Error (RMSE)

Root mean-squared error is the square root of mean-squared-error. This method exaggerates the estimated error—the difference between the estimated value and observed value (actual value). The Root Means Squared Error (RMSE) is computed as:

$$\text{RMSE} = \sqrt{\frac{1}{n} \left(\sum_{i=1}^n (x - y)^2 \right)}$$

iii. Average Relative Error (AvRE)

The average relative error (AvRE) was also calculated using the following equation:

$$\text{AvRE} = \left[\frac{1}{N} \sum_{i=1}^N \left(\frac{P_i - O_i}{O_i} \right) * 100 \right]$$

3.5.6 Organic Carbon (OC)

The Percentage of organic carbon was estimated by following the Walkley and Black (1934) method.

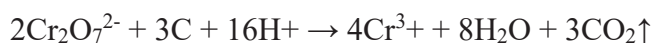
Reagents required:

- 1N potassium dichromate: 49.04 g of AR grade $K_2Cr_2O_7$ was dissolved in 500 ml of distilled water and volume made up to 1 liter
- Orthophosphoric acid (85%) or sodium fluoride
- Concentrated sulphuric acid (36N)
- 0.5N ferrous ammonium sulphate
- Diphenyl indicator

Procedure:

- To analyse the organic carbon, the soil samples were air-dried in shade and grounded with wooden pestle and mortar.
- 1g of 0.2mm size grounded soil sample was taken and put into 500ml dry conical flask.
- 10ml of 1N potassium dichromate and 20ml of concentrated sulphuric acid was added.
- The flask was swirled a little for 30 minutes and then 200ml of distilled water and 10ml of orthophosphoric acid was added slowly.
- 1ml of diphenyl indicator was added.
- The contents were titrated against 0.5N ferrous ammonium sulphate in a 50ml burette until the contents turned green.
- A blank was run simultaneously. Using the blank and the sample values the organic carbon content was calculated.

Equation:



1 mL of 1 N Dichromate solution is equivalent to 3 mg of carbon

Where the quality and normality of the acid/dichromate mixture used are as stated in the method, the percentage of carbon is determined from the following equation 5:

Calculations:

1 ml of 1 N $K_2Cr_2O_7$ = 0.003 g of organic carbon

$$\text{Organic carbon in soil} = \frac{10 \times (B-S) \times 0.003 \times 100\%}{B \times \text{Weight of soil}}$$

S= Sample titration value

B= Observation of blank sample

Interpretation of results for organic carbon:

- (i) < 0.50 % - Low
- (ii) 0.50 to 0.75% - Medium
- (iii) > 0.75% - High

3.5.7 Total Organic Carbon: The total organic carbon in soil was determined using the automatic elemental analyser (Vario EL, Elementar Analysen systeme GmbH, Hanau, Germany). The main principle behind the total organic carbon analyser is the catalytic oxidation combustion technique in the presence of a high temperature of 720°C. The generated carbon dioxide is measured by a non-dispersive infrared sensor

Total soil organic carbon stock ($Mgha^{-1}$) = [TOC (%) / 100] × Bulk density (Mgm^{-3}) × depth (m) × 10,000 (m^2ha^{-1}).

3.5.8. Aggregate associated carbon: It was determined for each aggregate class by using TOC analyzer.

3.5.9. Carbon pool

For analysis of carbon fractions, the soil samples were air-dried in shade and grounded with wooden pestle and mortar.

The oxidizable organic carbon content of soils was determined using the wet oxidation method given by Walkley and Black (1934). The different fraction was estimated by following the modified Walkley and Black as described by Chan et al. (2001) using 5,10

and 20 ml of concentrated H₂SO₄ which results in three acid aqueous solutions 0.5:1, 1:1 and 2:1 and its corresponded to 12.0N, 18.0N and 24.0N of H₂SO₄ respectively, when compared with total organic carbon, allowed its separation into four different fractions of decreasing oxidation capacity.

Pool1: (very labile)- The amount of organic carbon oxidized by 12.0 N H₂SO₄.

Pool 2: (labile)- The difference in the amount of carbon oxidized by 18N and that by 12N H₂SO₄.

Pool 3: (Less labile)-The difference in the amount of carbon oxidized by 24N and that by 18.0 N H₂SO₄.

Pool 4: (Non-labile)- The difference in total carbon and carbon oxidized by 24.0N

Labile fraction = Pool 1+Pool 2

Recalcitrant fraction = Pool 3+Pool 4

3.5.10 Carbon Mineralization

Sample preparation: The soil samples were taken from 0-5 cm, 5-15 cm, 15-30 cm, and 30-45 cm soil depth with the help of the core sampler. The moisture content of the soil samples was fixed to 60% of the water-filled pore space (WFPS).

WFPS (%) = (Gravimetric moisture content) / (Total pore volume × Volume of cylinder)

Total pore volume = 1 - (Bulk density) / (Particle density)

Incubation study: All the soil cores were kept in a closed airtight glass container with a lid and septum (Figure 3.6). Then these containers were placed in an incubator at 30°C temperature for 28 days. The rate of carbon mineralization was monitored by taking the gas samples at 30 minute interval with a 250 ml syringe at 1, 4, 7, 11, 18, 21, 28 days. After taking the sample the containers were opened for 30 min for free gas exchange and oxygen supply, also the moisture content of the samples was adjusted with distilled water on a weight basis. In Gas-chromatography the emitted CO₂ from the soil sample was converted to methane through the process of methanization and it was measured by the

Flame Ionization Detector (FID). The results obtained from Gas-chromatography were converted to equivalent amount of soil carbon by taking consideration of molecular weight of CO₂.

Kinetics model of Carbon mineralization:

The decomposition kinetics was fitted with a first order exponential model. The first-order kinetic model is expressed as:

$$C_m = C_0 (1 - e^{-kt})$$

where C_m-cumulative CO₂-C emission, C₀- potentially mineralizable C (mgg⁻¹), k- decomposition rate constant (day⁻¹), and t time of incubation (days)

All the statistical analysis was done using SPSS and excel.



Figure 3.6: CO₂ sampling for monitoring carbon mineralization

4. RESULTS

To determine the effects of porosity and pore size distribution on carbon mineralization under conservation agricultural practices, the experiment was conducted in Main Block (MB) of experimental farm of ICAR- Indian Agricultural Research Institute, New Delhi. Samples were collected from conventional tillage (CT), permanent narrow bed (PNB), permanent broad bed (PBB), PBB along with crop residue (PBB+R), PNB along with crop residue (PNB+R), zero tillage (ZT) and ZT with residue retention of previous crops (ZT+R) at the time of sowing and harvesting of maize crop. Soil parameters like bulk density (BD), infiltration rate, saturated hydraulic conductivity, soil aggregation, porosity and pore size distribution by X-ray Computed tomography, total organic carbon (TOC) were studied. To determine the effects of porosity and pore size distribution on carbon mineralization, incubation study was conducted in laboratory. The results obtained from the current experiment and laboratory study are presented in the following sections.

4.1. Weather condition during the study period

The study was conducted during the standard meteorological week from 27-43. The meteorological condition prevailed during the study period is given in Table 4.1. The mean maximum and minimum temperature during the study period was 33.55 and 24.39°C with an average temperature of 28.97°C. The total rainfall received during the study period was 569.5 mm and 89 % of which was received in the month of July and August. Total bright sunshine hour (BSS) was 521.7 hours with a weekly average value of 4.39 hr. The mean RH and wind speed during the study period were 74.76% and 3.67 km/hr.

4.2. Effect of different conservation agricultural practices on porosity and pore size distribution and other soil parameters at sowing and harvesting of maize crop

Table 4.1: Meteorological Parameters during the study period (July–October, 2019)

Meteorological week	Tmax (°C)	Tmin (°C)	Tmean (°C)	Rhmean (%)	Rainfall (mm)	Sunshine (hours)	EP (mm)	AWS (Kmph)
27	37.7	28.8	33.2	72.7	0.2	4.2	6.5	4.7
28	38.2	29.3	33.7	65.6	7.5	0.8	6.1	8.0
29	33.1	25.0	29.1	80.6	215.1	2.4	4.3	4.0
30	33.6	26.8	30.2	81.7	60.5	2.5	3.5	4.6
31	33.6	27.4	30.5	79.6	7.6	2.6	4.1	4.0
32	33.5	27.5	30.5	81.1	66.6	5.4	4.8	5.6
33	31.9	25.2	28.5	83.4	106.6	2.7	3.7	5.7
34	34.1	25.9	30.0	78.2	46.8	5.4	4.3	2.6
35	35.2	26.8	31.0	73.7	8.6	3.1	4.7	2.6
36	34.9	27.1	31.0	76.1	0.0	3.4	4.3	2.2
37	35.7	26.8	31.3	76.4	6.2	4.9	4.6	2.5
38	33.6	24.6	29.1	76.3	2.6	5.4	4.2	3.5
39	32.0	23.7	27.8	71.6	0.2	4.3	3.5	3.7
40	31.8	21.2	26.5	69.7	41.0	13.8	3.0	3.4
41	32.1	19.1	25.6	67.2	0.0	3.1	3.4	2.3
42	32.8	18.6	25.7	65.6	0.0	4.2	3.3	2.0
43	30.9	15.2	23.1	69.4	0.0	6.4	3.3	2.1
Mean	33.55	24.39	28.97	74.76	35.58	4.39	4.07	3.67
Standard error	0.45	0.97	0.67	1.48	14.37	0.73	0.19	0.41
Standard deviation	1.81	3.89	2.68	5.94	57.49	2.91	0.78	1.64
Kurtosis	1.61	0.61	0.29	1.281	6.11	7.39	1.53	1.91
Skewness	1.03	-1.16	-0.58	-0.25	2.34	2.34	0.97	1.35
Range	7.24	14.06	10.65	17.86	215.1	13.01	3.11	6.06
Maximum	38.18	29.3	33.74	83.43	215.1	13.78	6.08	8.01
Minimum	30.94	15.24	23.09	65.57	0	0.77	2.97	1.96

4.2.1 Porosity and pore size distribution

Based on the resolution of the instrument, pores were classified into four classes i.e. Class 1: 60-100 μm ; Class 2: 110-500 μm , Class 3: 510-1500 μm and Class 4: >1500 μm . As the resolution of the instrument was 60 μm , pores smaller than 60 μm were not detected by the instrument and considered as micropores. Pores greater than 60 μm were considered as macropores. From (Figure 4.1. a, b, c, d, e, f, g) it is clear that in 0-5 cm soil depth, there was huge variation in number of soil pores among the treatments. The height of soil slice used for scanning was 2 cm from 0-5 cm soil layer. Total numbers of detected pores were highest in ZT+R, followed by PBB+R (Table 4.2) and lowest number of pores was found in PBB followed by ZT. In CT plots, the number of detected pores were increased 12.38% higher than ZT whereas, number of detected pores was higher by 88, 18.28 and 92.74 % in PBB+R, PNB+R and ZT+R, respectively. All the residue applied plots were on an average of 84.93% more number of detected pores than non-residue applied plots. In class 1, ZT +R had 5.7% more pores than PBB+R. In class 4, detected pores were maximum in CT and were minimum in ZT. Average pore under CA based plots in class 4 (i.e. 1500 μm) were 5 as compared to 105 in CT. In class 2, residue applied plots had 60.40 % more pores than non-residue applied plots. Under CT, 197.12 % of more pores were found in class 3 than all CA based plots. If we see the pore volume in different classes among all the treatments (Table 4.3), maximum was obtained in CT and it was more 44.19% more as compared to other CA based treatments. Pore volumes of class 3 and 4 were highest in CT. Though the number of pores in class 1 was maximum in all the treatments except ZT and CT but their contribution to total detected pore volume was on an average only 0.27% for all the treatments. Volume contribution to the total detected volume was maximum from class 2 i.e. 110-1000 μm which was on an average 80.46% for all the treatments. The detected macroporosity ranged from 7.62 to 15.17 % for all the treatments with an average value of 11.58 % (Table 4.4). Detected macroporosity was maximum in CT and the trend followed was: CT>PBB+R>ZT+R>PNB+R>PNB>ZT>PBB. Micro porosity was highest in PBB (83.21%) and lowest was in CT (64.71%).

Table 4.2: X-ray computed tomography detected numbers of pores in each class in 0-5 cm of soil depth

Treatments	Class 1	Class 2	Class 3	Class 4	Total detected macropores
CT	30405	62599	517	105	93626
PNB	47115	41484	116	9	88724
PNB+R	62636	47887	217	5	110745
PBB	49854	32565	135	6	82560
PBB+R	112953	62917	275	9	176154
ZT+R	119397	60865	198	4	180464
ZT	17939	35266	103	0	83308

Table 4.3: X-ray computed tomography detected volume of pores in each class in 0-5 cm of soil depth

Treatments	Class 1	Class 2	Class 3	Class 4	Total macro pore volume(mm ³)
CT	6.50	5446.113	532.51	184.8	6169.93
PNB	10.08	3609.10	119.48	15.84	3754.51
PNB+R	13.40	4166.16	223.51	8.8	4411.88
PBB	10.66	2833.15	139.05	10.56	2993.43
PBB+R	24.17	5473.77	283.25	15.84	5797.04
ZT+R	25.55	5295.25	203.94	7.04	5531.78
ZT	10.25	3068.14	106.09	0	3184.49

Table 4.4: Micro and macro porosity in 0-5 cm of soil depth

Treatments	Total X-ray computed tomography derived Macroporosity (%)	Microporosity of total porosity (%)
CT	15.71	64.71
PNB	9.56	78.47
PNB+R	11.24	75.58
PBB	7.62	83.21
PBB+R	14.76	68.88
ZT+R	14.09	68.61
ZT	8.11	80.52

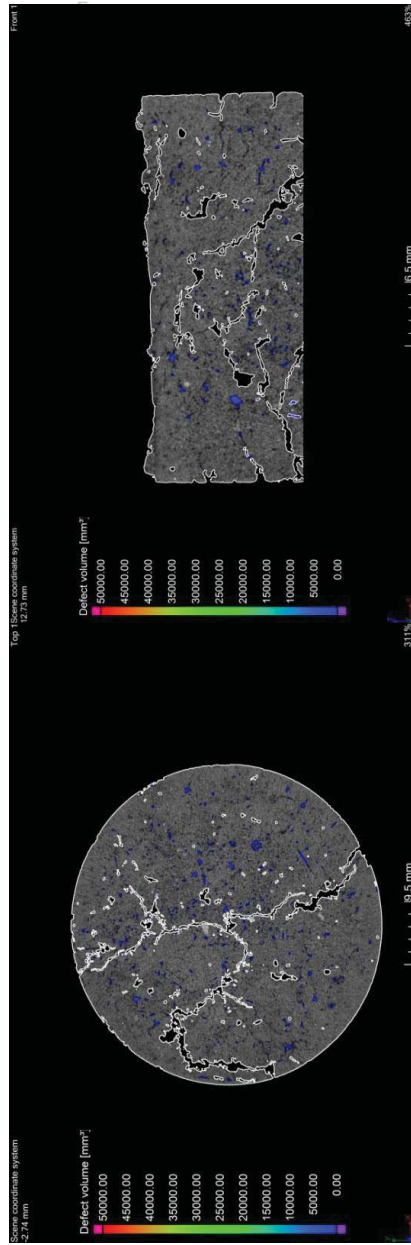


Figure 4.1.a. X-ray computed tomography scanned image of 0-5 cm soil in CT

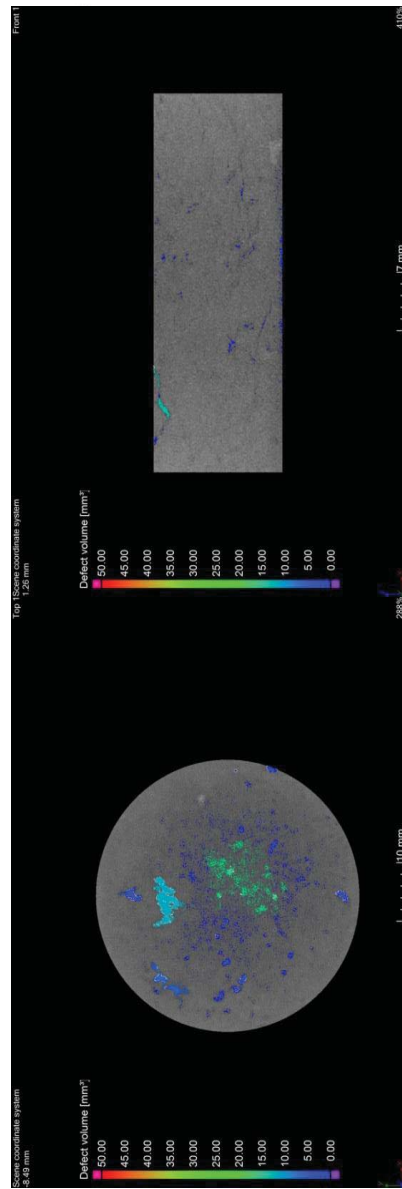


Figure 4.1.b. X-ray computed tomography scanned image of 0-5 cm soil in ZT

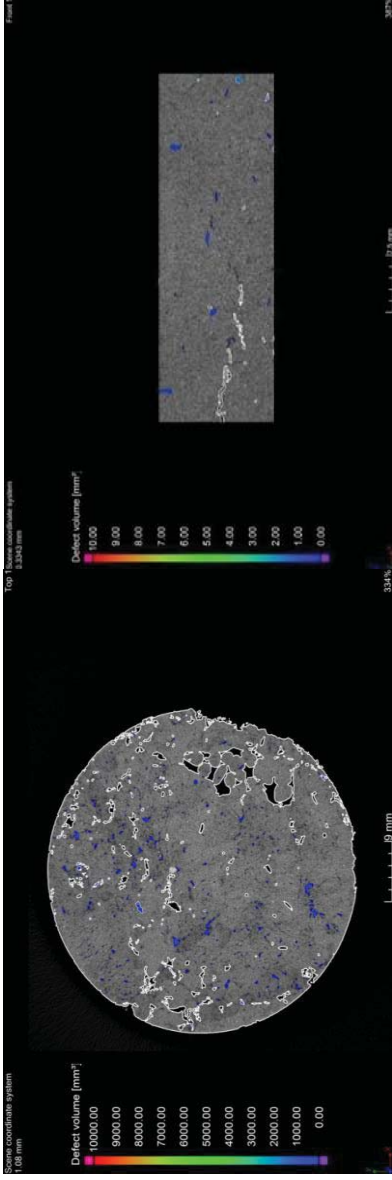


Figure 4.1.c. X-ray computed tomography scanned image of 0-5 cm soil in PNB+R

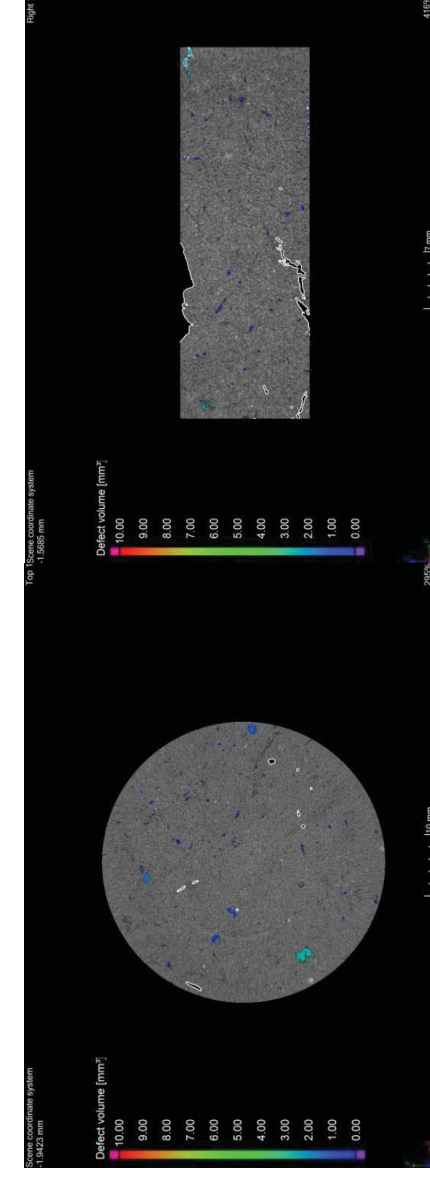


Figure 4.1.d. X-ray computed tomography scanned image of 0-5 cm soil in PNB

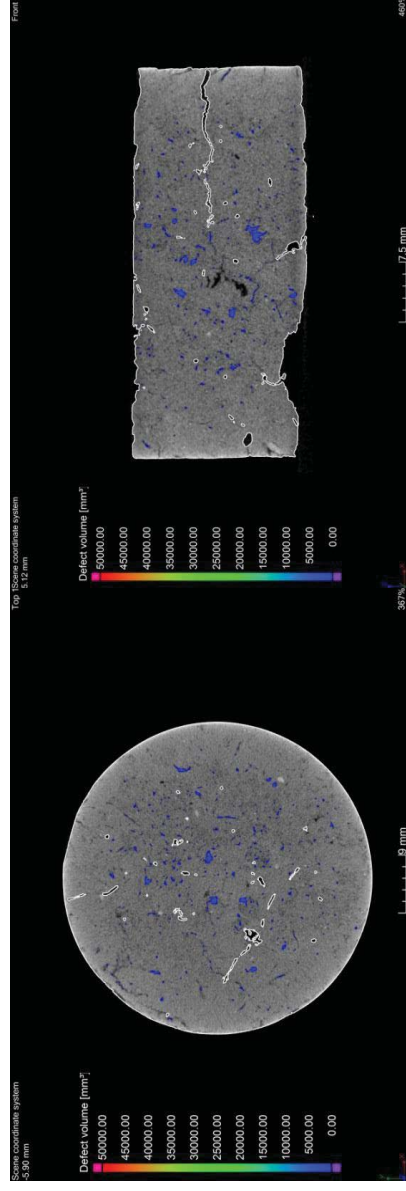


Figure 4.1.e. X-ray computed tomography scanned image of 0-5 cm soil in PBB+R

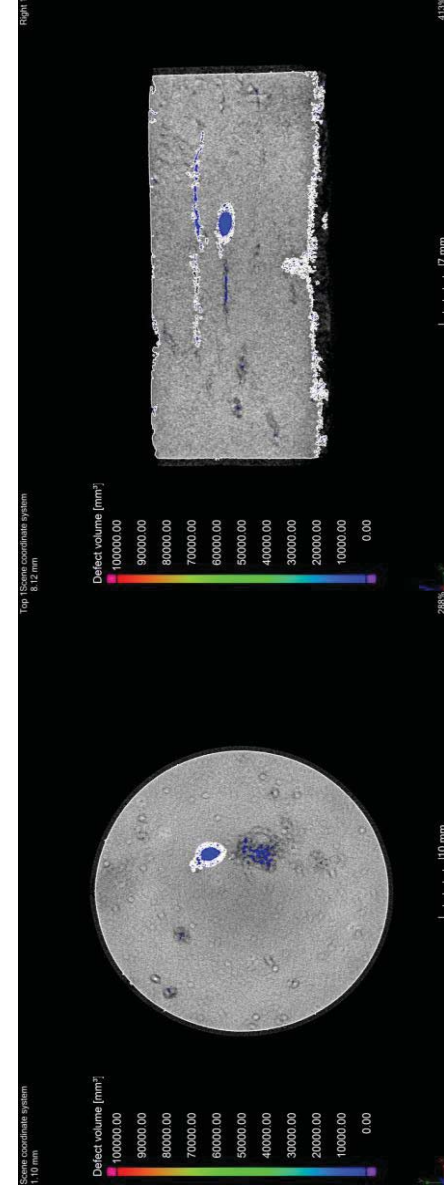


Figure 4.1.f. X-ray computed tomography scanned image of 0-5 cm soil in PBB

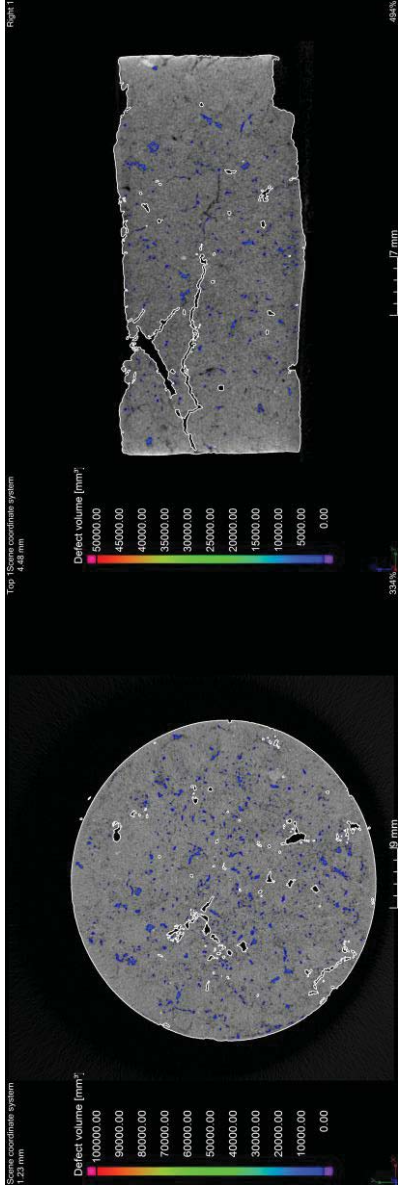


Figure 4.1.g. X-ray computed tomography scanned image of 0-5 cm soil in ZT+R

In 5-15 cm soil depth, height of the soil slice was 5 cm (Figure 4.2 a, b, c, d, e, f, g,) The total number of detected pores was maximum in PBB+R and minimum was in PNB (Table 4.5). Average numbers of pores in different treatments were 147643. Average numbers of pores in all CA based treatments were 153095 which was 3.67% more as compared to CT. The average numbers of detected pores were 188357 in residue applied plots (PBB+R, PNB+R and ZT+R) which was around 59.85 % more than the non-residue applied pores (i.e. PNB, PBB and ZT). The average numbers of detected pores were 91545 in class 1, 55610 in class 2, 470 in class 3 and 20 in class 4, respectively among all the treatments. The numbers of detected pores present in different treatments followed the order: CT>ZT>PBB+R>>ZT+R>PBB>PNB>PNB+R. The average contribution of class 3 (i.e. 510-1500 μ m) pores was only 0.32% to total detected pores and macroporosity detected was only around 2% contribution of class 4 i.e. > 1500 mm pores was 0.0132%. Though the contribution of Class 1 pores to total numbers of detected pores was maximum but its contribution to total detected pore volume was only 0.36 % (Table 4.6). Average contribution of class 2 pores to total detected pore volume was around 90%. X-ray computed tomography derived detected macroporosity was maximum in CT plot which was 7.04% and in all the CA based plots average detected macroporosity was 4.22% (Table 4.7). As the soil depth increased, the amount of detected porosity decreased irrespective of treatments. Undetected macroporosity was 83.18 % whereas, undetected macroporosity was more in all CA based plots varying from 89.17 to 91.18%. Sphericity increased irrespective of treatments as the soil depth increased from 0-5 cm to 5-15 cm. Compactness also increased in all the treatments as the soil depth increased

Table 4.5: X-ray computed tomography detected numbers of pores in each class in 5-15 cm of sol depth

Treatments	Class 1	Class 2	Class 3	Class 4	Total detected macropores
CT	41425	71599	1817	93	114934
PNB	45913	51386	230	9	97538
PNB+R	63879	51234	235	8	115356
PBB	99857	52548	214	8	152627
PBB+R	173465	54239	455	9	228168
ZT+R	168352	52973	213	10	221548
ZT	47921	55289	121	0	103331

Table 4.6: X-ray computed tomography detected volume of pores in each class in 5-15 cm of soil depth

Treatments	Class 1	Class 2	Class 3	Class 4	Total macro pore volume (mm ³)
CT	8.86	6229.11	1871.51	163.68	8273.168
PNB	9.82	4470.58	236.9	15.84	4733.147
PNB+R	13.67	4457.35	242.05	14.08	4727.158
PBB	21.36	4571.67	220.42	14.08	4827.545
PBB+R	37.12	4718.79	468.65	15.84	5240.405
ZT+R	36.02	4608.65	219.39	17.6	4881.668
ZT	10.25	3810.14	124.63	0	3945.028

Table 4.7: Micro and macro porosity in 5-15 cm of soil depth

Treatments	Total X-ray computed tomography derived Macroporosity (%)	Microporosity of total porosity (%)
CT	7.04	83.18
PNB	4.02	90.79
PNB+R	4.02	91.18
PBB	4.10	90.50
PBB+R	4.45	90.23
ZT+R	4.15	89.68
ZT	4.20	89.17

Sphericity of all pores in class 1 was 0.81 in all the treatments. The sphericity ranged from 0.22 to 0.81 in class 2, 0.21 to 0.53 in class 3 and 0.11 to 0.55 in class 4, respectively, for all the treatments. As the depth progress the sphericity increases irrespective of the treatments especially in class 3 and class 4 (Table 4.8). The compactness of class 3 and class 4 increases as the depth progress (4.9).

Table 4.8: Sphericity of pores in each class in 0-5 and 5-15 cm of soil depth

Treatments	Class 1	Class 2	Class 3	Class 4	Class 1	Class 2	Class 3	Class 4
CT	0.81	0.28-0.81	0.25-0.49	0.17-0.49	0.81	0.21-0.81	0.26-0.57	0.11-0.25
PNB	0.81	0.24-0.81	0.22-0.49	0.13-0.49	0.81	0.27-0.81	0.23-0.53	0.12-0.23
PNB+R	0.81	0.31-0.81	0.23-0.5	0.12-0.55	0.81	0.29-0.81	0.25-0.57	0.14-0.54
PBB	0.81	0.25-0.81	0.24-0.48	0.12-0.54	0.81	0.26-0.81	0.21-0.56	0.11-0.56
PBB+R	0.81	0.22-0.81	0.21-0.5	0.13-0.41	0.81	0.27-0.81	0.24-0.57	0.12-0.53
ZT+R	0.81	0.26-0.81	0.24-0.49	0.14-0.53	0.81	0.29-0.81	0.22-0.56	0.13-0.56
ZT	0.81	0.3-0.81	0.27-0.53	0.11-0.53	0.81	0.29-0.81	0.21-0.53	0.11-0.54

Table 4.9: Compactness of pores in each class in 0-5 cm and 5-15cm soil depth

Treatments	Class 1	Class 2	Class 3	Class 4	Class 1	Class 2	Class 3	Class 4
CT	1.91	0.01-1.04	0.01-0.27	0-0.25	1.91	0.01-1.04	0.01-0.35	0-0.36
PNB	1.91	0.01-1.04	0-0.28	0-0.24	1.91	0.01-1.04	0-0.38	0-0.02
PNB+R	1.91	0.01-1.04	0.01-0.27	0-0.26	1.91	0.01-1.04	0.01-0.33	0-0.39
PBB	1.91	0.01-1.04	0-0.31	0-0.28	1.91	0.01-1.04	0.01-0.36	0-0.36
PBB+R	1.91	0.01-1.04	0.01-0.30	0-0.28	1.91	0.01-1.04	0.01-0.34	0-0.38
ZT+R	1.91	0.01-1.04	0-0.29	0-0.29	1.91	0.01-1.04	0-0.38	0-0.38
ZT	1.91	0.01-1.04	0.01-0.28	0-0.24	1.91	0.01-1.04	0.01-0.36	0-0.37

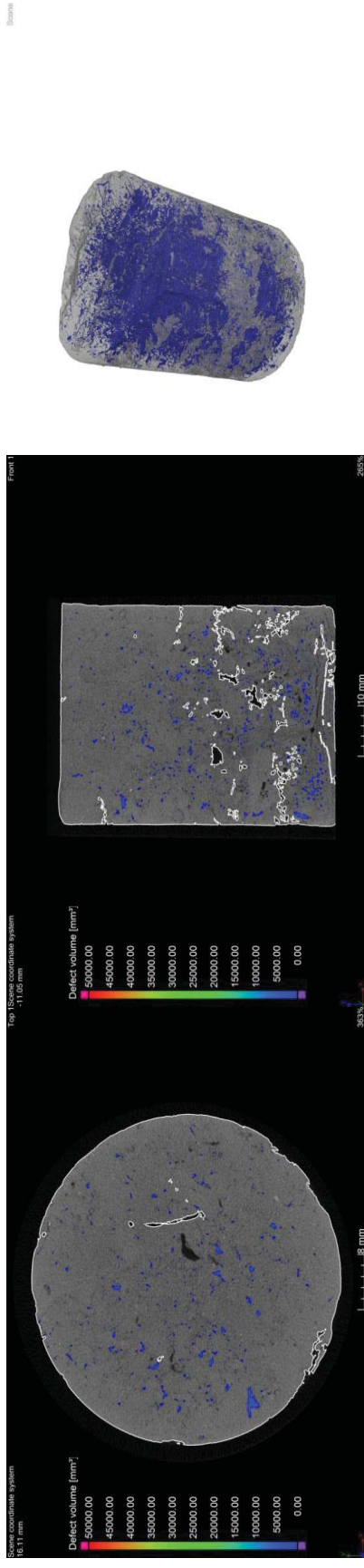


Figure 4.2.a. X-ray computed tomography scanned image of 5-15 cm soil in CT

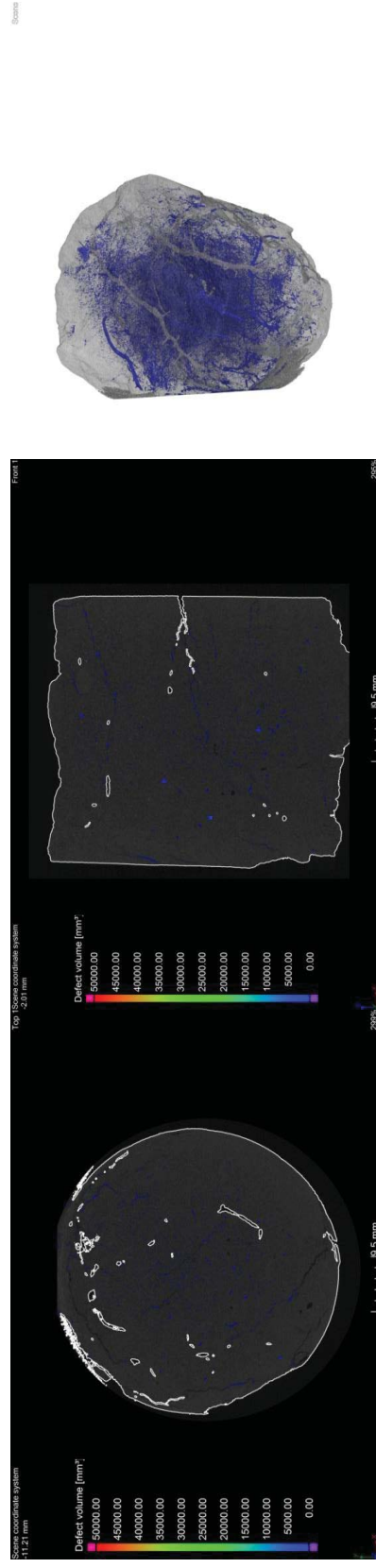


Figure 4.2.b. X-ray computed tomography scanned image of 5-15 cm soil in PNB

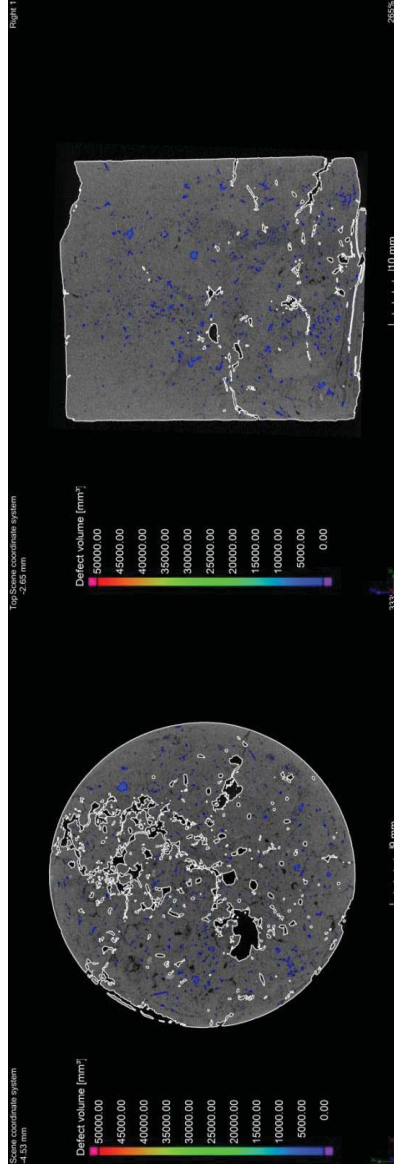


Figure 4.2.c. X-ray computed tomography scanned image of 5-15 cm soil in PNB+R

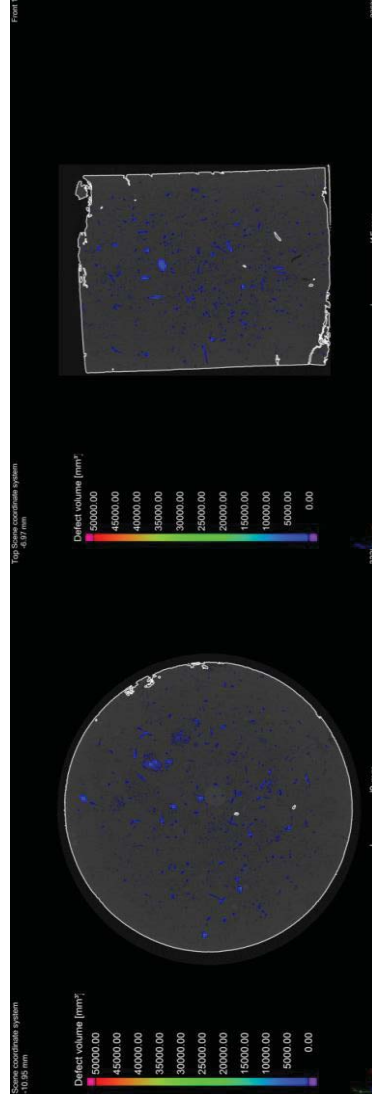


Figure 4.2.d. X-ray computed tomography scanned image of 5-15 cm soil in ZT+R

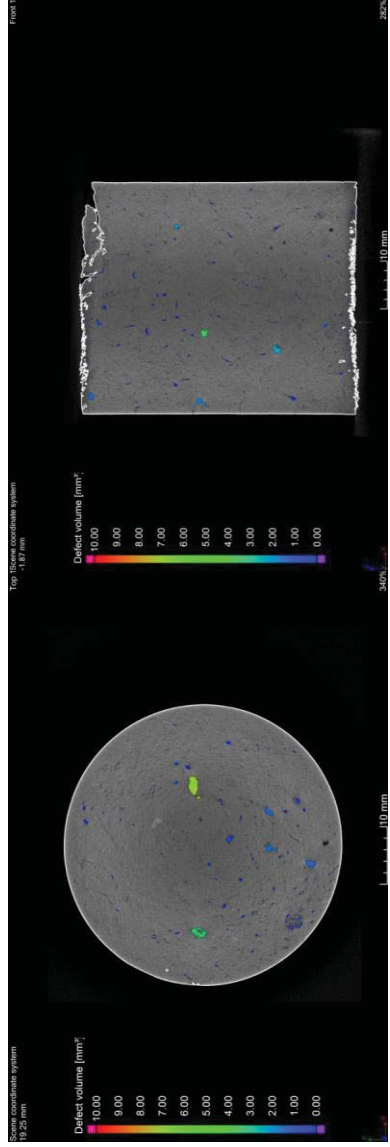


Figure 4.2.e. X-ray computed tomography scanned image of 5-15 cm soil in PBB+R

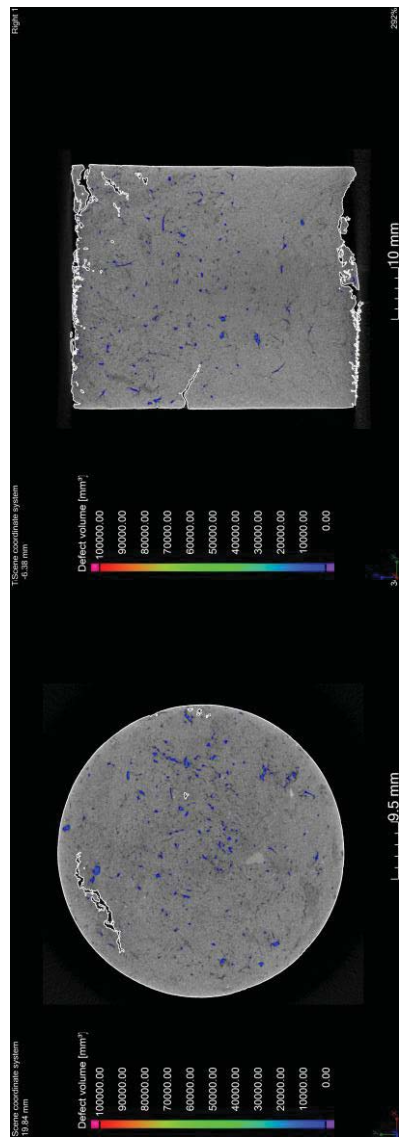


Figure 4.2.f. X-ray computed tomography scanned image of 5-15 cm soil in ZT

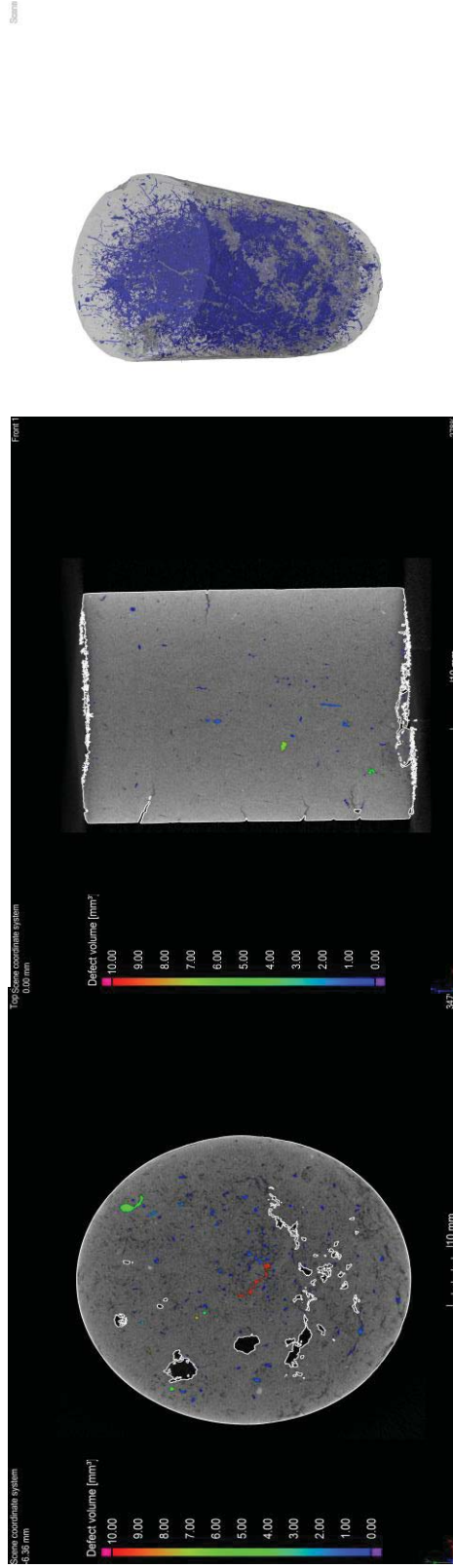


Figure 4.2.g. X-ray Computed Tomography scanned image of 5-15 cm soil in PBB

As there was limitation of scanning, we could not scan all the samples in 15-30 and 30-45 cm of soil depth (Figure 4.3 a, b and 4.4 a, b). For 15-30 and 30-45 cm of soil depth, we could scan only CT and PBB+R. From the Table 4.10, 4.11, as the depth increased, number and volume of detected pores decreased irrespective of treatments. In 15-30 cm of soil depth, the numbers of detected pores of PBB+R in class 1 was 11.94% more than CT. Contribution of class 1 pores to the total numbers of detected pores were 84.61 % in CT and 81.85% in PBB+R. As the smaller sizes pore increased with depth, the macroporosity detected were 2.94 % for CT and 3.14% for PBB+R (Table 4.12). A volume contribution of class 2 pores was 96.11% in CT and 97.50% in PBB+R. In 30-45 cm of soil depth, detected pore numbers and volumes reduced drastically. Also, macroporosity detected was only around 2%.

Table 4.10: X-ray computed tomography detected numbers of pores in each class in 15-30 and 30-45 cm of soil depth

Treatments	Class 1	Class 2	Class 3	Class 4	Total detected macropores
15-30 cm					
CT	70319	12762	17	7	83105
PBB+R	62814	13909	12	3	76738
30-45 cm					
CT	57215	9303	3	0	66521
PBB+R	53243	8677	1	0	61921

Table 4.11: X-ray computed tomography detected numbers of pores in each class in 15-30 and 30-45 cm of soil depth

Treatments	Class 1	Class 2	Class 3	Class 4	Total macro pore volume(mm ³)
15-30 cm					
CT	15.04827	1110.294	17.51	12.32	1155.172
PBB+R	13.4422	1210.083	12.36	5.28	1241.165
30-45 cm					
CT	12.24401	809.361	3.09	0	824.695
PBB+R	11.394	754.899	1.03	0	767.323

Table 4.12: Micro and macro porosity in 15-30 and 30-45 cm of soil depth

Treatments	Total X-ray computed tomography derived Macroporosity (%)	Microporosity of total porosity (%)
15-30 cm		
CT	2.94	92.50
PBB+R	3.16	92.79
30-45 cm		
CT	2.10	94.07
PBB+R	1.95	94.58

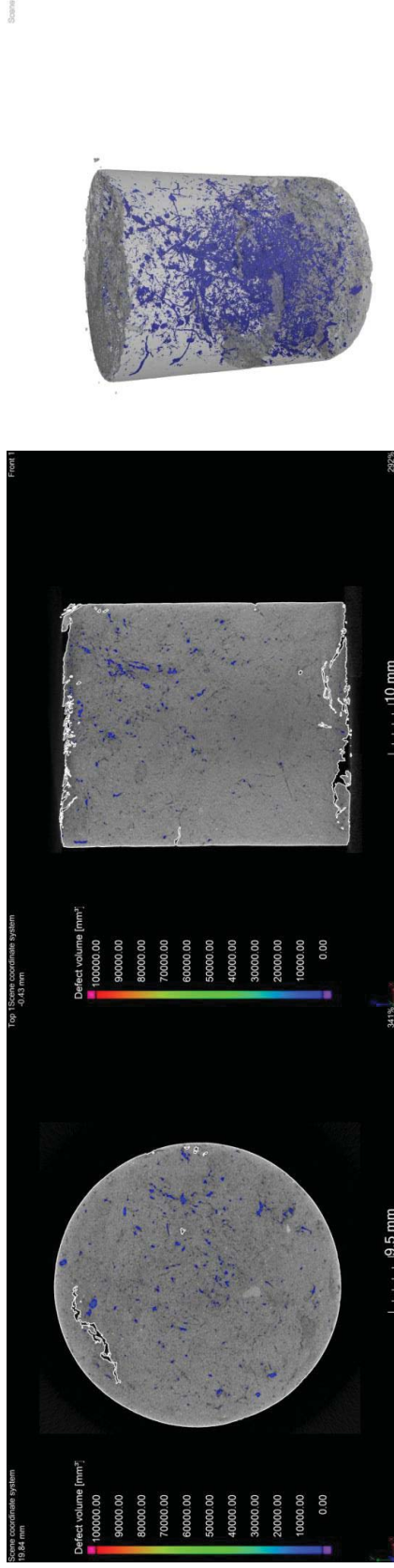


Figure 4.3.a. X-ray computed tomography scanned image of 15-30 cm soil in PBB+R

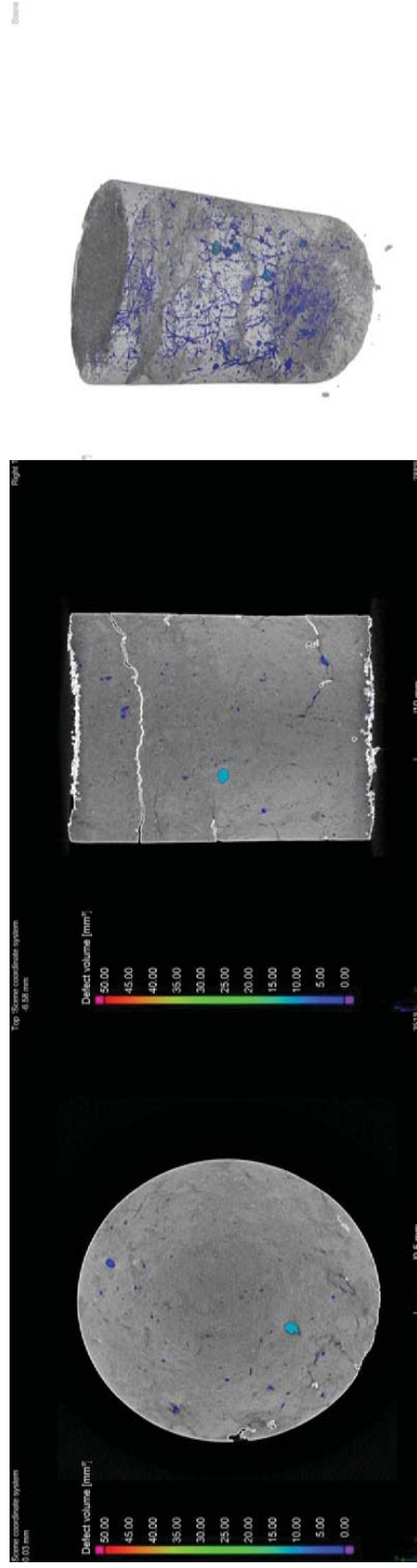


Figure 4.3.b. X-ray computed Tomography scanned image of 15-30 cm soil in CT

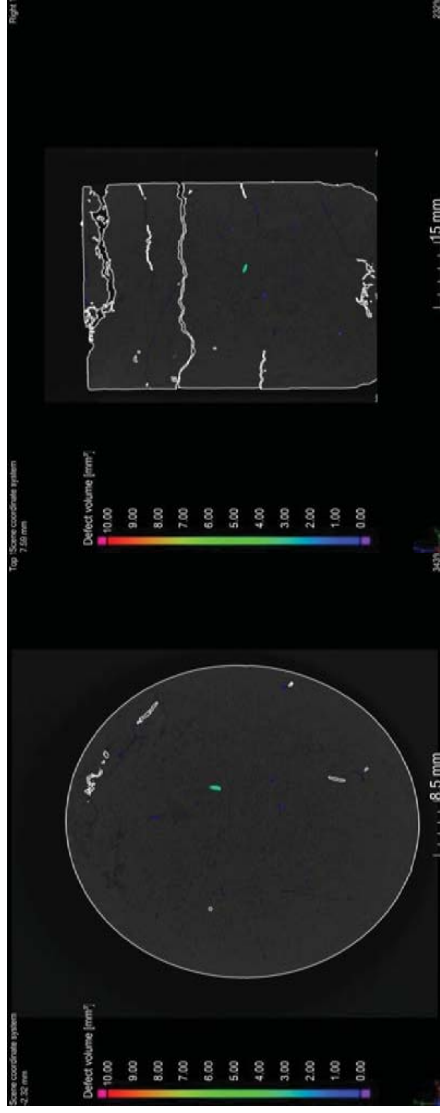


Figure 4.4.a. X-ray Computed Tomography scanned image of 30-45 cm soil in PBB+R

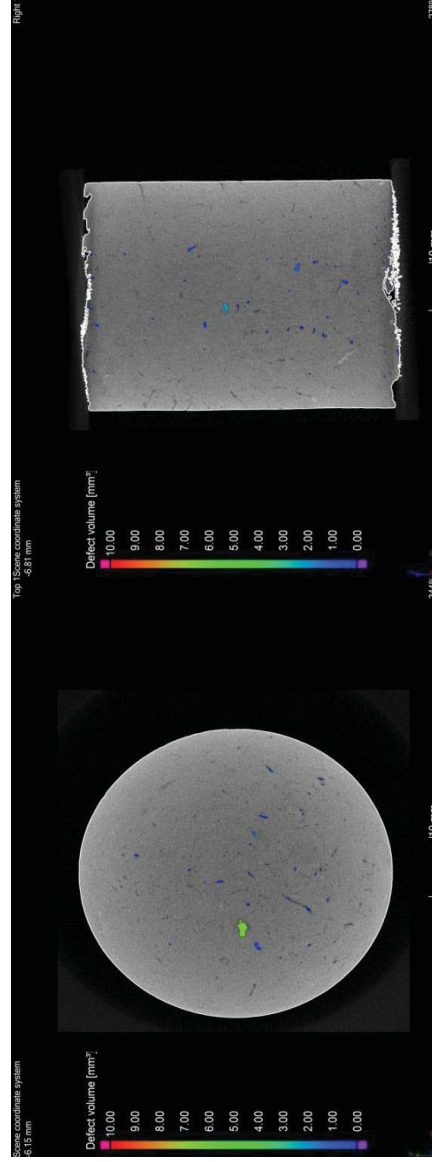


Figure 4.4.b. X-ray computed tomography scanned image of 30-45 cm soil in CT

4.2.2. Bulk density

BD values of 0-5 cm of soil layer at the time of sowing showed that ZT had highest BD (1.55 Mg m^{-3}) and significantly different from CT and PBB+R (Table 4.13). BD was lowest in PBB+R (1.39 Mg m^{-3}), followed by PNB+R (1.43 Mg m^{-3}). In PBB+R, BD was 8 and 15% lower than CT and ZT. There was no significant difference in BD values among PBB, PNB+R and ZT+R. At the time of harvesting, in 0-5 cm soil, highest BD of 1.61 Mg m^{-3} was obtained in ZT and it was significantly different from CT, PBB, PBB+R, PNB and PNB+R (Table 4.13). The lowest BD was observed in PBB+R (1.44 Mg m^{-3}) followed by PNB+R (1.46 Mg m^{-3}) but they were not significantly different. The BD value in PBB+R was 4.9 % lower than CT and 12.6 % lower than ZT. Though BD in ZT+R was not significantly different from ZT but ZT+R had 3.3% lower BD than ZT. In CT, BD value was 11 % lower than ZT. The average increase in BD from sowing to harvesting was 5.05% with a range of 0.7-11.7% among all the treatments. In 5-15 cm soil depth, BD was lowest in PBB+R and PNB+R during sowing (Table 4.13). Highest value of BD was obtained in ZT and it was 11 % higher than PBB+R and PNB+R. CT had 6.9 % higher BD than PBB+R and PNB+R. The BD in PBB and PNB was not significantly different. In ZT+R, BD was 0.04 Mg m^{-3} lower than ZT. At the time of harvesting, the BD followed the same trend among the treatments and PBB+R and PNB+R was almost same BD. In CT the BD increased by 3.8 % from sowing to harvesting. In 15-30 cm soil, during sowing, there was not significant difference in BD among CT, PBB, PNB and ZT+R. PBB+R had significantly lowest BD (1.49 Mg m^{-3}) than other treatments and ZT had significantly higher BD than other treatments (Table 4.14). For different depths, the results showed that in general residue applied plot had lower BD as compared to non-residue applied plot. During harvesting at 15-30 cm soil depth, BD value was not significantly different in CT, PNB, ZT+R and PBB. Lowest BD value of 1.57 Mg m^{-3} was obtained in PBB+R and it was not significantly different from PNB+R. Highest BD value of 1.67 Mg m^{-3} was obtained in ZT and it was significantly different from all other treatments. In all the treatments, there were not much changes in BD from sowing to harvesting. In 30-45 cm soil depth, average BD was 1.69 and 1.72 Mg m^{-3} for all the treatments at the time of sowing and harvesting, respectively. But no significant difference in BD was obtained among the treatments during the sowing and harvesting.

Table 4.13: Bulk Density 0-5 and 5-15 cm sowing and harvesting of maize crop

Treatments	0-5 cm		5-15 cm	
	Sowing	Harvesting	Sowing	Harvesting
CT	1.47b	1.51b	1.54c	1.6c
PBB	1.45ab	1.50b	1.50b	1.52b
PBB+R	1.39a	1.44a	1.44a	1.44a
PNB	1.47b	1.48ab	1.49b	1.51b
PNB+R	1.43ab	1.46a	1.44a	1.45a
ZT	1.55c	1.61c	1.62e	1.63d
ZT+R	1.46ab	1.58c	1.58d	1.61c
SE	±0.021	±0.014	±0.005	±0.005
LSD (P < 0.05)	0.044	0.044	0.0114	0.012
CV	9.13%	9.6%	10.1%	10.49%

Table 4.14: Bulk Density 15-30 and 30-45 cm soil during sowing and harvesting of maize crop

Treatments	15-30 cm		30-45 cm	
	Sowing	Harvesting	Sowing	Harvesting
CT	1.61c	1.65b	1.71a	1.72a
PBB	1.59bc	1.63b	1.73a	1.71a
PBB+R	1.49a	1.57a	1.69a	1.69a
PNB	1.61c	1.62b	1.66a	1.69a
PNB+R	1.58b	1.59a	1.66a	1.69a
ZT	1.71d	1.68c	1.73a	1.75a
ZT+R	1.59bc	1.63b	1.73a	1.74a
SE	±0.01	±0.01	±0.02	±0.02
LSD (P < 0.05)	0.16	0.02	0.06	0.04
CV	9.14%	8.92%	7.27%	8.02%

4.2.3. Effects of different CA practices on infiltration characteristics

The initial infiltration rate was highest (22.93 cmhr⁻¹) in PBB+R and was lowest (7.64 cmhr⁻¹) in CT (table 4.15). The initial infiltration rates of PNB, PNB+R, PBB and ZT were 15.29 cmhr⁻¹, 20.37 cmhr⁻¹, 17.20 cmhr⁻¹ and 11.46 cmhr⁻¹, respectively (Table 4.15). The steady state infiltration rate was highest (7.49cmhr⁻¹) in PBB+R and the time

taken to reach was 2.58 hrs. The lowest steady state infiltration rate of 2.11 cmhr⁻¹ was observed in CT plot and time taken to reach was 1.62 hrs. The result showed that in all the residue applied plots initial infiltration rate and steady state infiltration rates were higher. Cumulative infiltration of all the treatments followed the order: PBB+R>PNB+R>PBB>PNB>ZT>CT.

Table 4.15: Characteristics of infiltration of soil under different CA treatments

Treatments	Initial infiltration rate (cm hr ⁻¹)	Steady state infiltration rate (cm hr ⁻¹)	Time to reach steady state (hr)	Cumulative infiltration (cm)
CT	7.64	2.11	1.62	5.00
PNB	15.29	4.78	1.17	20.61
PNB+R	20.37	5.12	2.33	22.64
PBB	17.20	6.02	1.50	13.79
PBB+R	22.93	7.49	2.58	27.17
ZT	11.46	3.50	2.17	11.15

4.2.3.1. Effects of different CA treatments of selected infiltration model parameters

The model parameters for Kostiakov, Green Ampt and Philip models were estimated by fitting the observed infiltration data (Table 4.16). The ‘a’ parameter in Kostiakov model signifies the initial infiltration rates. The estimated ‘a’ value was highest in PBB+R, followed by PNB+R and lowest value was obtained in CT (Table 4.16 and Figure 4.5). The ‘a’ value was 197.5 and 310 % higher in PBB and PBB+R as compared to CT. The observed initial infiltration rate also follows the same trend. The negative sign of ‘b’ parameter in Kostiakov model indicated reduced rate of infiltration with time. The lowest ‘b’ value (-0.346) in PBB+R indicates that the infiltration phenomena was prolonged which might be due to the more porous environment. The higher values of ‘b’ of -0.457, -0.473 and -0.548 in CT, PNB and PNB+R, respectively, indicated that steady state infiltration is obtained in shorter period. In Green and Ampt model, i_c is the steady state infiltration which was found to be highest (8.47 cmhr⁻¹) in PBB+R and was lowest (1.88 cmhr⁻¹) in CT (Table 4.16 and Figure 4.6). The model estimated i_c values followed the order: PBB+R>PBB>PNB>PNB+R>ZT>CT. The model underestimated the steady state infiltration rate for CT and PNB+R. Steady state infiltration rates were overestimated for

all other treatments. Likewise, ‘B’ parameter ($\text{cm}^2 \text{hr}^{-1}$) in Green Ampt model, which is dependent on initial infiltration rate was lowest in CT (3.9) (Table 4.16). These results are in line with experimentally measured value. Sorptivity (S) parameter ($\text{cm hr}^{-0.5}$) of Phillip model is related to initial soil water content and porous environment of the CT (16.23) (Table 4.16 and Figure 4.7). Higher value of ‘S’ in residue applied plots was due to more porous environment and better soil structure than other treatments (Rai *et al.*, 2018). ‘K’ value of Phillip model is saturated hydraulic conductivity. Highest values of ‘K’ was obtained in PBB+R followed by PBB> PNB>PNB+R>CT which are almost similar to the experimentally observed values (data not shown). Model estimated ‘K’ value for ZT was found to be negative which indicated some unexplained error caused due to poor curve fitting of the model.

Table 4.16: Parameters and coefficients of various infiltration models obtained by least-square fitting to the infiltration data for different CA treatments.

Treatments	Kostiakov model		Green and Ampt model (1911)		Philip model	
	a (cm/hr)	b	i_c (cm/hr)	B (cm^2/hr)	S ($\text{cm hr}^{-1/2}$)	K (cm/hr)
CT	2.57	-0.45	1.88	3.91	16.22	0.59
PNB	5.48	-0.47	5.17	23.1	34.24	1.47
PNB+R	8.84	-0.54	4.94	61.47	67.33	0.61
PBB	7.55	-0.39	7.23	16.77	33.74	3.82
PBB+R	10.55	-0.34	8.47	31.59	43.61	4.98
ZT	4.86	-0.37	3.84	8.16	25.41	-0.84

4.2.3.2. Performance evaluation of the infiltration models

The performance evaluation of three infiltration models was done by calculating coefficients of determination (R^2), Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Average Relative Error (AvRE) (Table 4.17). Greater values of R^2 and lesser value of RMSE, MAE and ARE indicate the well performance of the model. Values of R^2 varied between 70-98%, RMSE between 0.33-3.16, MAE between 0.27-2.72 and AvRE between 0.1- 21.93% in different models. From (Table 4.17), it is clear that Kostiakov, Green Ampt and Philip models performed well for CT and five CA practices.

But the negative value of ‘K’ obtained from the physical process-based Philip model shows the poor capability of statistical techniques in determining model coefficients.

Table 4.17: Evaluation of infiltration models under different conservation agriculture

Treatments	R ²	RMSE	MAE	AvRE
Kostiakov model				
CT	0.96	0.33	0.96	0.43
PNB	0.95	1	0.72	0.33
PNB+R	0.93	3.16	2.72	21.93
PBB	0.9	1.64	1.2	0.79
PBB+R	0.97	1	0.78	0.19
ZT	0.98	0.34	0.27	0.1
Green and Ampt model				
CT	0.91	0.56	0.53	4.32
PNB	0.83	1.49	1.30	4.86
PNB+R	0.82	2.24	1.91	7.83
PBB	0.70	2.29	2.13	6.5
PBB+R	0.84	2.07	1.81	4.06
ZT	0.89	0.85	0.76	3.3
Philip model				
CT	0.96	0.33	0.27	0.99
PNB	0.93	0.93	0.79	2.31
PNB+R	0.92	1.45	1.18	4.01
PBB	0.84	1.66	1.49	3.78
PBB+R	0.94	1.25	1.06	1.88
ZT	0.95	0.56	0.45	0.59

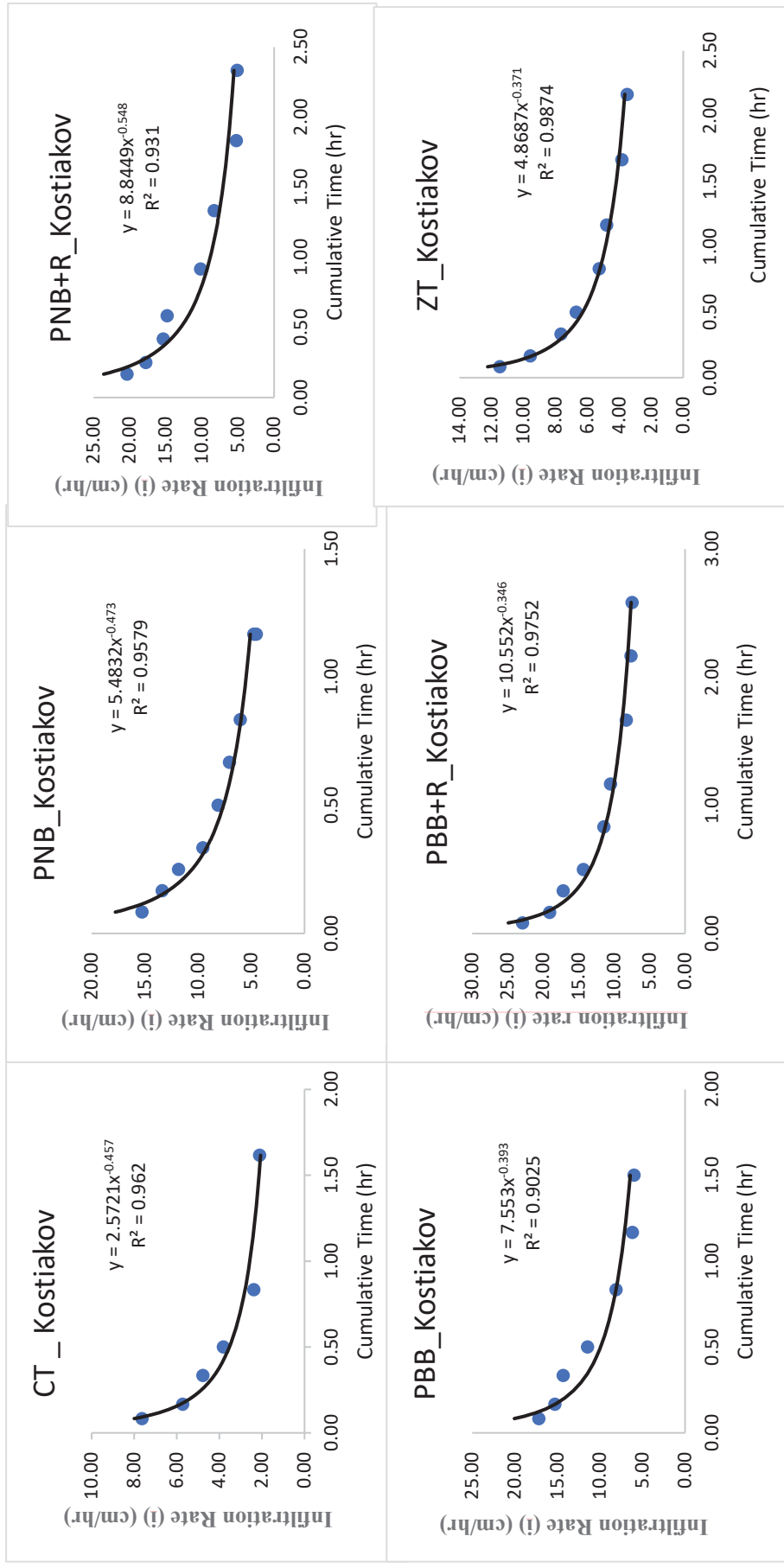


Figure 4.5: Infiltration rate (i) vs cumulative time (t) for Kostiakov model

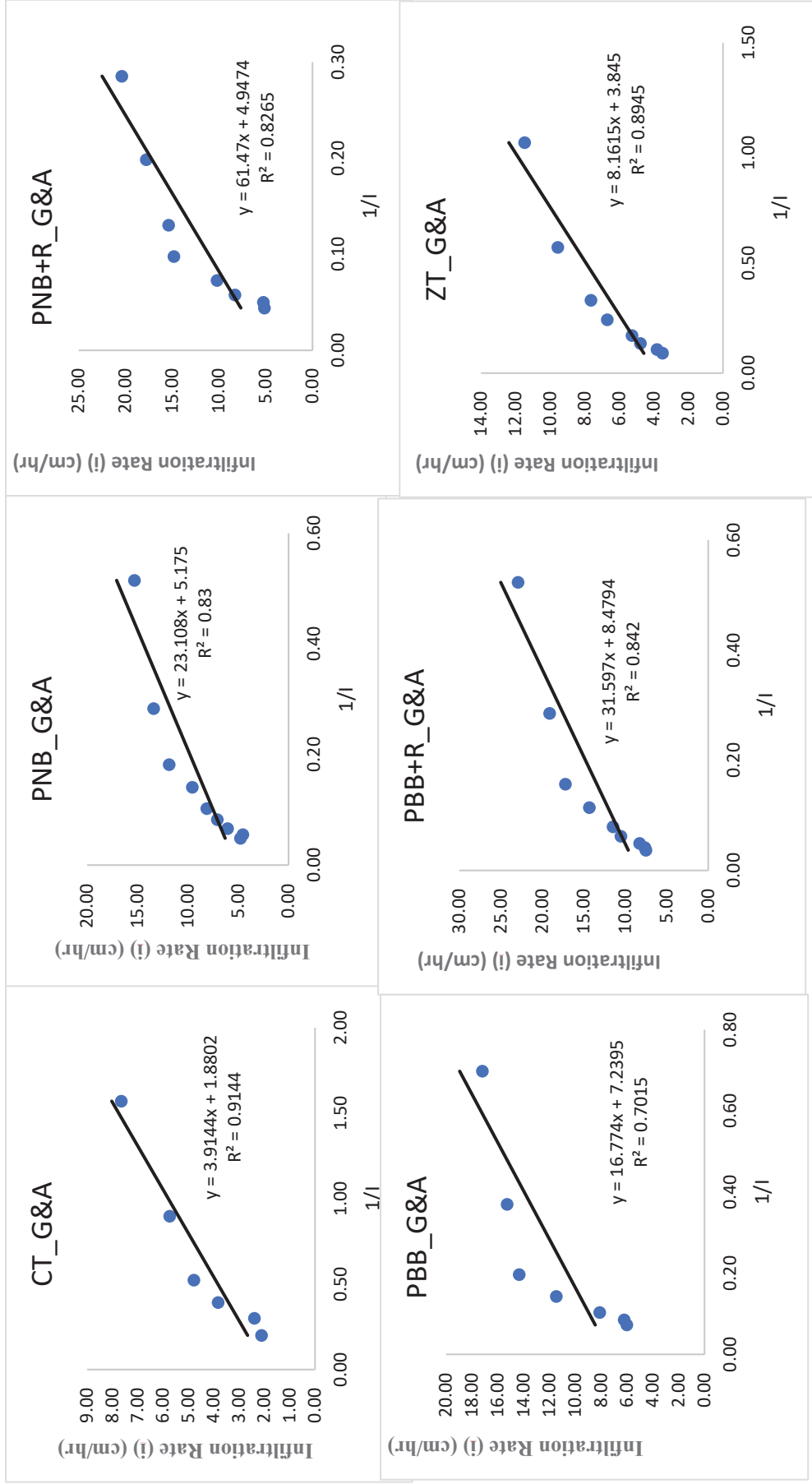


Figure 4.6: Infiltration rate (i) vs $1/I$ /Cumulative Infiltration (I) for Green and Ampt model

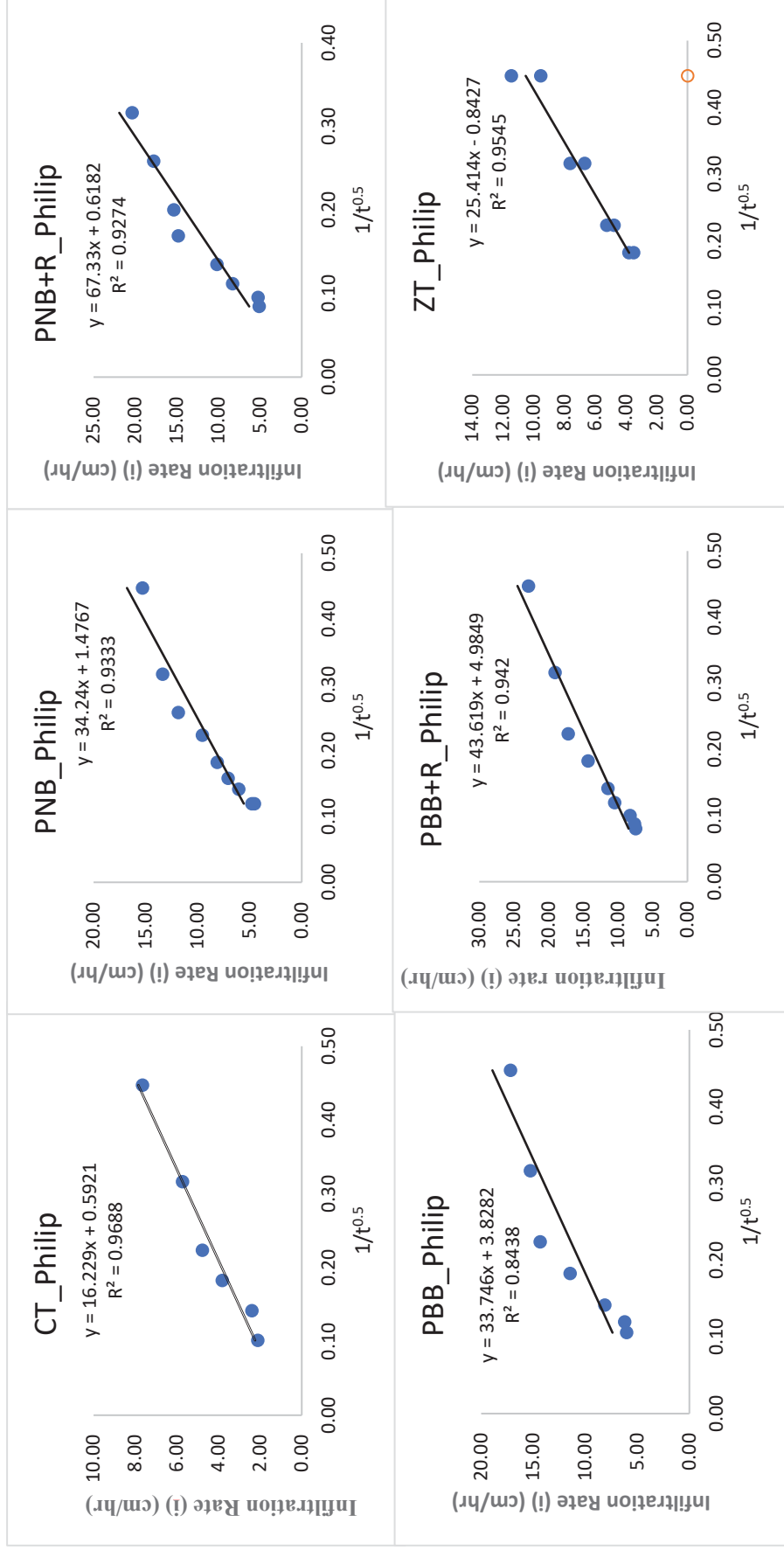


Figure 4.7: Infiltration rate (*i*) vs $1/t^{0.5}$ for Philip mode

4.2.4. Effects of different CA practices on saturated hydraulic conductivity

In 0-15 cm of soil depth, highest saturated hydraulic conductivity (HC) of 69.85 cm/day was obtained in PBB+R and lowest value of 55.30 cm/day was observed in ZT at the time of sowing (Table 4.18). The trend of HC was as follows: PBB+R>PNB+R>PNB>PBB>ZT+R>CT>ZT. In ZT plot, HC was 9.4% lower than CT and 26.3, 23.25 and 4.8% lower than PBB+R, PNB+R and ZT+R, respectively. The HC was significantly lower in ZT than all other treatments except for ZT+R. The HC values were higher for the residue applied plots. During harvesting, the HC values decreased for all the treatments. At harvesting, HC was not significantly different among CT, PNB and ZT+R. But PBB and PBB+R were significantly different. The HC of PBB+R and PNB+R were 66.75 and 65.45 cm/day which did not vary significantly. The HC values decreased from 4.1 to 16.1 % as the crop progressed from sowing to harvesting. At 15-30 cm soil depth, though lowest HC of 53.84 cm/day was obtained in ZT but it was not significantly different from CT which had a value of 55.60 cm/day at the time of sowing. PBB+R had significantly higher HC of 20.8 and 24.7% than CT and ZT, respectively.. PNB+R had 5.29 cm/day of lower HC than PBB+R. At the harvesting time, HC decreased irrespective of treatments. HC of CT and ZT were not significantly different.

But HC values of PBB and PBB+R were significantly different. The average decrease in HC from sowing to harvesting was 2.34 % among the treatments. Like surface layer (0-15 cm), HC values were higher in residue applied plots during sowing and harvesting. Average HC values of 30-45 cm of soil depth were 60.33 and 49.08 cm/day during sowing and harvesting (Table 4.18).

Table 4.18: HC 0-15, 15-30 and 30-45 cm of soil depth at sowing and harvesting

Treatments	0-15 cm		15-30 cm		30-45 cm	
	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
CT	60.52b	57.63b	55.61a	53.33a	55.61a	46.01a
PBB	65.47c	62.28c	62.2b	59.83c	62.2b	49.23b
PBB+R	69.86d	66.75d	67.17c	64.69d	67.17c	50.87b
PNB	67.96cd	58.18b	57.19a	55.73ab	57.19a	50.13b
PNB+R	68.16cd	65.45d	61.88b	59.26bc	61.88b	50.07b
ZT	55.31a	51.12a	53.84a	51.86a	53.84a	45.94a
ZT+R	57.97ab	57.66b	64.44bc	61.24cd	64.43bc	51.33b
SE	±1.16	±0.84	±1.23	±1.26	±1.08	±0.64
LSD (P < 0.05)	2.80	2.04	2.97	2.96	2.61	1.56
CV	10.95%	11.76%	9.47%	10.04%	10.97%	14.95%

4.2.5. Effects of different CA practices on mean weight diameter

In 0-5 cm soil depth, highest mean weight diameter (MWD) of 1.0 was obtained in PBB+R and lowest MWD of 0.82 was obtained in CT at the time of sowing (Table 4.19). The difference in MWD of PBB+R and PNB+R was not significantly different. Average MWD of all treatments during sowing was 0.93 and 0.9 at the time of harvesting. The MWD was 18.6 and 16.6% higher than CT. The MWDs of PBB, ZT and ZT+R were not significantly different from each other. All the residue applied plots were higher MWD than non-residue plots. In surface 0-5 cm soil, lowest MWD (0.78) was found in CT and highest MWD (1.0) was obtained in PBB+R during harvesting. MWD of PBB+R was significantly higher than all other treatments CT had 26.6% and 7.6% lower MWD than PBB+R and ZT, respectively.. The residue applied plots had 6.2% more MWD in sowing than non residue applied plots, whereas, average MWD at the time of harvesting was 7.46 % more in residue applied plots. In 5-15 cm soil depth, average MWD of all treatments was 0.87 and 0.79 at the time of sowing and harvesting, respectively (Table 4.19). Lowest MWD was found to be 0.79 in CT which was significantly lower than all other treatments. CT had a range of 5.0- 14.6 % lower MWD than all other treatments. Similarly, at

harvesting, lowest MWD of 0.71 was found in CT which was significantly lower than all other treatments. In general, there were reductions of MWD with a range from 0.07 to 0.12 when crop progressed from sowing to harvesting. There was mean 5.12 % reduction in MWD from 0-5 to 5-15 cm soil depth at sowing time. Similarly, at the time of harvesting MWD reduced by 12.17% from 0-5 to 5-15 cm soil depth.

Although lowest MWD of 0.63 was observed in CT (15-30 cm soil depth), but significantly higher MWD were found in residue applied plots (i.e. PBB+R, PNB+R and ZT+R at the time of sowing. Mean MWD of all the treatments was 0.77 in 15-30 cm soil depth CT had 5.7 -12.4% lower MWD than all other treatments. Residue applied plots had 3.76 % higher MWD than non-residue plots (i.e. ZT, PNB, PBB). At the time harvesting, mean MWD of all the treatments was 0.73 in 15-30 cm soil depth. MWD was not significantly different among CT, ZT, PBB and PNB but PBB+R had significantly higher MWD than all other treatments. At harvesting residue applied plots had 7.63% more MWD than non-residue plots. There was a mean reduction of 4.58% in MWD from sowing to harvesting in 15-30 cm soil depth. The trend of MWD in 30-45 cm of soil depth during sowing and harvesting followed the same trend as that in 15-30 cm soil depth. Although, there was 18.8 and 19.54 % reduction in MWD during sowing and harvesting as the soil depth increased from 15-30 to 30-45 cm.

4.2.6. Effects of different CA practices on aggregation

In 0-5 cm soil depth, lowest macroaggregates was found in CT and it was significantly lower than the other treatments at the time of sowing (Table 4.20). PBB+R had highest macroaggregates of 54.92 g/100g soil. Macroaggregates of PBB, PNB+R and ZT+R were not significantly different from each other. Though macroaggregates of ZT was 5.96 g/100g soil more than CT. Residue applied plot had soil more macroaggregates than non-residue plots (i.e. ZT, PNB and PBB). At the time of harvesting, highest macroaggregates of 53.88g/100g soil was obtained in PBB+R which was significantly higher than the other treatments. The macroaggregates were 1.67 to 12.12% lower from sowing to harvesting in 0-5 cm soil depth. More macroaggregates was found at the time of sowing in all the treatments.

Table 4.19: Mean Weight Diameter (mm) in 0-5, 5-15, 15-30 and 30-45 cm of soil depth at sowing and harvesting

Treatment	0-5 cm		5-15cm		15-30 cm		30-45 cm	
	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
CT	0.8a	0.79a	0.79a	0.71a	0.69a	0.67a	0.53a	0.51a
PBB	0.94c	0.94b	0.91b	0.83b	0.77ab	0.69a	0.61ab	0.53ab
PBB+R	1.01d	1.05c	0.93b	0.86b	0.82b	0.82b	0.66b	0.59b
PNB	0.89b	0.87b	0.84ab	0.76ab	0.78ab	0.71a	0.56ab	0.53ab
PNB+R	0.98d	0.93b	0.92b	0.84b	0.80b	0.74ab	0.58ab	0.56b
ZT	0.91bc	0.86ab	0.84ab	0.75ab	0.75ab	0.70a	0.54b	0.51a
ZT+R	0.94c	0.92b	0.89ab	0.77ab	0.80b	0.76ab	0.62ab	0.53ab
SE	±0.008	±0.026	±0.026	±0.34	±0.029	±0.028	±0.028	±0.015
LSD(P < 0.05)	0.02	0.062	0.062	0.01	0.076	0.062	0.062	0.044
CV	11.29%	12.28%	12.28%	11.47%	12.07%	9.33%	9.33%	17.92%

Table 4.20: Macroaggregates and microaggregates in 0-5 and 5-15 of soil depth at sowing and harvesting

Treatment	0-5 cm				5-15 cm			
	Macroaggregates (g/100g soil)		Microaggregates (g/100g soil)		Macroaggregates (g/100g soil)		Microaggregates (g/100g soil)	
	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
CT	43.39a	42.49a	24.30a	22.63a	42.09a	37.69a	20.96a	19.56a
PBB	49.87bc	49.05d	31.20ab	29.53ab	45.31ab	42.54c	22.90ab	21.61abc
PBB+R	54.92c	53.88e	34.57b	33.20b	47.65b	43.21c	27.27b	24.99c
PNB	47.82ab	45.54bc	27.40ab	25.74ab	46.09ab	41.14bc	23.28ab	21.32ab
PNB+R	52.11bc	47.30cd	31.37ab	29.71ab	47.17b	42.86c	24.72ab	23.01abc
ZT	49.35b	44.02ab	26.41ab	24.75a	44.95ab	39.21ab	22.03ab	20.56ab
ZT+R	51.39bc	47.40cd	29.77ab	28.11ab	46.24ab	43.30c	23.51ab	23.36bc
SE	±1.64	±0.89	±2.80	±2.4	±1.32	±0.81	±1.60\	±1.08
LSD (P <0.05)	3.96	2.15	6.785	5.8	3.18	1.96	3.87	2.61
CV	10.83%	10.5%	18.35%	18.4%	11.97%	12.8%	20.3%	17.92%

The average microaggregates content was 29.29 and 27.66 g/100g soil at sowing and harvesting in 0-5 cm soil depth (Table 4.20). Significantly higher microaggregates were obtained in PBB+R (i.e. 34.57 g/100g soil) and significantly lower microaggregates were obtained under CT (i.e. 34.58 g/100g soil) in 0-5 cm of soil depth at the time of sowing. Similar trend in microaggregates content of soil was obtained at the time of harvesting. At the time of harvesting, microaggregates reduced by 4.14-7.36% among all the treatments as compared to sowing. Average macroaggregates of all the treatments were 45.64 and 41.42 g/100g in 5- 15 cm of soil depth at the sowing and harvesting time. Significantly lower macroaggregates of 42.1 g/100g soil were found in CT as compared to PBB+R and PNB+R in 5-15 cm of soil depth at the time of sowing. The macroaggregates content of PBB+R and PNB+R were not significantly different. At the time of sowing and harvesting, macroaggregates was on an average 9.12 and 13.79 % more in 0-5 cm soil depth as compared to 5-15 cm soil. CT and PBB+R had 20.96 and 27.27 g/100g soil microaggregates in 5-15 cm soil depth at the time of sowing. There was no significant difference in microaggregates content among other treatments at sowing. The microaggregates content followed the same trend at harvesting. There was around 6.67 % decrease in microaggregates content in 5-15 cm soil depth from sowing to harvesting. Macroaggregates content of ZT and CT were 33.76 and 35.45 g/100 g soil in 15-30 cm soil depth at the sowing time, though the values were not significant (Table 4.21). Highest macroaggregates of 45 g/100g soil was found in PBB+R but the value was not significantly different from PBB, PNB+R, PNB and ZT +R. In residue applied plot macroaggregates content was 11.62 % more than non-residue applied plot. At harvesting, lowest macroaggregates were found in CT (30.28 g/100g soil). Though macroaggregates content of PBB+R was more than PNB+R but the difference was not statistically significant. Average macroaggregates content for all the treatments at the time of sowing and harvesting were 40.82 and 32.93 g/100g soil. In general, macroaggregates content reduced in 15-30 cm of soil depth as compared to 0-5 and 5-15 cm of soil depth. Average microaggregates content of 15-30 cm soil was almost same at the time of sowing and harvesting. In 30-45 cm soil depth, the macro and microaggregates content followed the same trend at the sowing and harvesting time (Table 4.21)

Table 4.21: Macroaggregates and microaggregates in 15-30 and 30-45 cm of soil depth at sowing and harvesting

Treatment	15-30 cm				30-45 cm			
	Macroaggregates (g/100g soil)		Microaggregates (g/100g soil)		Macroaggregates (g/100g soil)		Microaggregates (g/100g soil)	
	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
CT	33.75a	30.28a	17.88a	17.91a	33.06a	27.58a	31.14a	27.98a
PBB	41.98b	33.94bc	21.82a	18.46ab	35.49ab	30.05ab	32.20a	28.10a
PBB+R	45.00b	35.26c	20.47a	21.85b	38.51b	32.22b	33.13a	30.82a
PNB	42.00b	31.38ab	19.87a	18.51ab	34.61ab	30.02ab	33.20a	27.23a
PNB+R	43.98b	34.72c	21.17a	19.46ab	35.90ab	30.74ab	31.51a	27.60a
ZT	35.45a	31.39ab	17.74a	20.56ab	35.90ab	29.18ab	32.56a	28.67a
ZT+R	43.60b	33.49bc	18.11a	19.75ab	37.01ab	30.48ab	32.20a	29.52a
SE	±1.95	±0.88	±1.85	±1.07	±1.54	±0.97	±1.17	±1.13
LSD (P < 0.05)	4.73	2.13	4.46	2.6	3.74	2.36	2.83	2.74
CV	14.68%	7.52%	27.68%	19.15%	12.96%	10.62%	27.49%	9.43%

All the BD, MWD, HC and macroaggregates data collected at the time of sowing and harvesting have been pooled and plotted. In Figure 4.8 blue dots represented the relationship between MWD and HC. The trend line showed a positive relation between MWD and HC, since HC increased with increase in MWD. Red dot represented the relationship between HC and BD. The trend line showed a negative relationship between these two parameters as the HC of soils decreased with increase in BD.. Though the R² value is less but trend line showed a good relationship among these parameters. Figure 4.9 showed the relationship of BD, macroaggregates and MWD. Blue dot showed the negative relationship between BD and MWD with R² value of 0.78. Whereas, red dots depicted the positive relationship between macroaggregates and MWD with a R² value of 0.52.

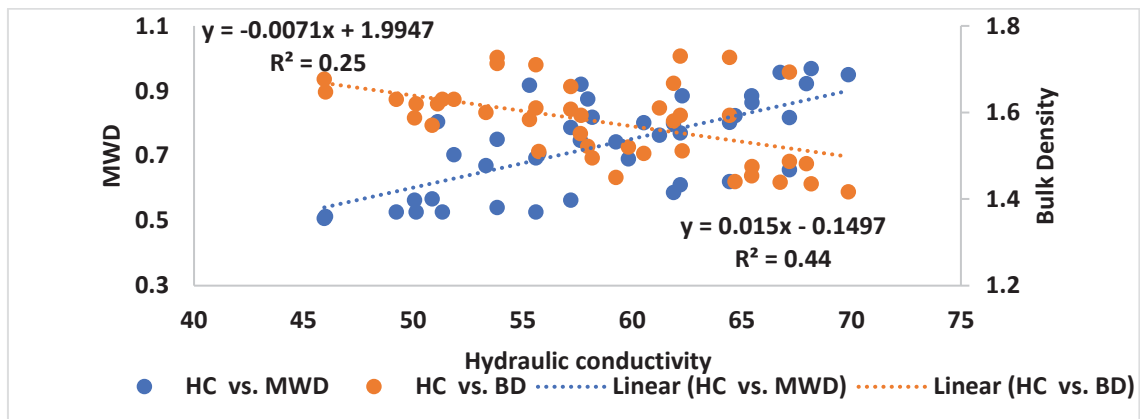


Figure 4.8: Relationship of HC, MWD and BD

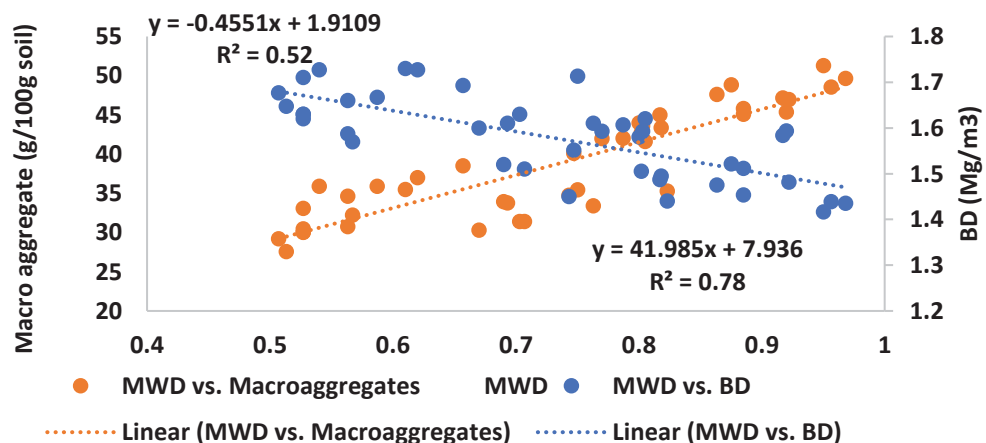


Figure 4.9: Relationship of MWD, Macroaggregates

4.2.7 Effect of conservation agriculture on carbon dynamics

In 0-5 cm soil depth, the average TOC content of all the plots was 9.3 g/kg soil. CT had lowest TOC value of 7.50 g/kg at the time of sowing and it was significantly lower than all other CA treatments (Table 4.22). PBB+R had significantly higher TOC than all other treatments. The magnitude of TOC content in different treatments followed the order: PBB+R>ZT+R>PNB+R>PBB>PNB>ZT>CT. The TOC content reduced slightly at the time of harvesting but followed the same trend as at the sowing. With respect to CT, TOC was 47.6 % in PBB+R, 28.1% in PNB+R, 36.1% in ZT+R, 25.4 % in PBB, 19.5 % in PNB and 14.7% in ZT in 0-5 cm soil depth. In 5-15 cm of soil depth, CT had lowest TOC and PBB+R had highest TOC values among all the treatments. Mean TOC values were 8.42 and 7.80 g/kg soil at the time of sowing and harvesting. TOC was 31.93% in PBB, 47.3% in PBB+R, 19.94% in PNB, 36.88% in PNB+R, 16.94% in ZT and 30.88% in ZT+R. At the time of harvesting the TOC content among different treatments followed the same trend. TOC was less by 11.9% in CT, 6.48% in PBB, 12.21% in PBB+R, 11.63% in PNB, 4.82% in PNB+R, 9.87% in ZT and 16.49% in ZT+R in 5-15 cm soil as compared to 0-5 cm soil depth. TOC content of PPB, PNB+R and ZT+R was not significantly different from each other. Average TOC contents of 15-30 cm soil layer were 6.56 and 6.11 g/kg soil at the time of sowing and harvesting. In 15-30 cm soil depth, TOC content of PNB+R and PBB+R was not significantly different but TOC content of CT plots was significantly different from other treatments. On an average, CT plot had 17.04% less TOC than all CA plots in 15-30 cm soil depth at the time of harvesting. During harvesting the trend was similar as that of sowing. In 30-45 cm soil depth, TOC content was significantly lower in CT but among the CA treatments, there was no significant difference in TOC content. Similar trend was found among different treatments at the time of harvesting.

In 0-5 cm soil depth, the highest carbon stock was observed in PBB+R with a magnitude of 7.65 Mg/ha at the time of sowing which was significantly higher than CT (Table 4.23). The percentage of increment in soil carbon stock compared to CT for other treatments was 24.22% in PBB, 40.36% in PBB+R, 20.55% in PNB, 24.58% in PNB+R, 21.65% in ZT and 35.77% in ZT+R.

Table 4.22: Total Organic Carbon (g/kg) of 0-5, 5-15, 15-30 and 30-45 coil depth at sowing and harvesting

Treatment	TOC (g/kg)											
	0-5 cm		5-15 cm		15-30 cm		30-45 cm					
	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting
CT	7.47a	7.23a	6.67a	6.43a	5.73a	5.37a	2.77a	2.77a	2.77a	2.77a	2.77a	2.77a
PBB	9.37bc	9.10b	8.80bc	8.17abc	6.40ab	5.93ab	3.30ab	3.30ab	3.30ab	3.30ab	3.30ab	3.03ab
PBB+R	11.03c	10.60c	9.83c	9.33c	7.47c	6.97c	3.27ab	3.27ab	3.27ab	3.27ab	3.27ab	3.20ab
PNB	8.93ab	8.70b	8.00ab	7.43ab	6.33ab	6.07abc	3.07ab	3.07ab	3.07ab	3.07ab	3.07ab	3.27ab
PNB+R	9.57bc	9.27bc	9.13bc	7.93bc	7.17c	6.70bc	3.13ab	3.13ab	3.13ab	3.13ab	3.13ab	3.17ab
ZT	8.57ab	8.23ab	7.80ab	7.43ab	6.10ab	5.23a	3.17ab	3.17ab	3.17ab	3.17ab	3.17ab	2.97ab
ZT+R	10.17bc	9.20bc	8.73bc	7.93abc	6.77bc	6.50bc	3.43b	3.43b	3.43b	3.43b	3.43b	3.40b
SE	±0.05	±0.05	±0.06	±0.05	±0.02	±0.03	±0.02	±0.02	±0.02	±0.02	±0.02	±0.02
LSD(P < 0.05)	0.42	0.10	0.14	0.12	0.05	0.07	0.04	0.04	0.04	0.04	0.04	0.04
CV	14.49%	17.01%	20.63%	19.3%	11.53%	16.40%	11.15%	11.15%	11.15%	11.15%	11.15%	12.45%

At the time of harvesting also the lowest and highest carbon stock was observed in CT and PBB+R with a magnitude value of 5.4 Mg/ha and 7.69 Mg/ha, respectively. There was around average 9.32% higher carbon stock in residue retention plot as compared to non-residue plots in sowing. In 5-15 cm soil depth the average soil carbon stock for all the treatments were 12.88 Mg/ha and 12.1 Mg/ha at sowing and harvesting, respectively. In this depth, carbon stock followed the same trend as 0-5 cm depth at both sowing and harvesting. Carbon stock was 29.22% in PBB, 39.61% in PBB+R, 16.69% in PNB, 28.44% in PNB+R, 25.05% in ZT and 36.50% in ZT+R as compared to CT in 5-15 cm at the time of sowing. Whereas, at the time of harvesting, carbon stock was 19.61% in PBB, 28.95% in PBB+R, 8.049% in PNB, 9.59% in PNB+R, 16.09% in ZT and 22.1% in ZT+R compared to CT. In 0-15 cm soil depth, carbon stock was 13.9% in CT, 30.61% in PBB, 31.23% in PBB+R, 21.13% in PNB, 17.19 % in PNB+R, 24.42 in ZT and 32.11 % in ZT+R as compared to 15-30 cm soil depth. At the time of harvesting, on an average 26.12% carbon stock was more in 0-15 cm soil depth as compared to 15-30 cm. In 15-30 cm soil depth the carbon stock was significantly lowest in CT compared to other treatments at the time of sowing. There was no significant difference in carbon stock in residue retention plots viz, PBB+R, PNB+R, and ZT+R in both sowing and harvesting. The increment in carbon stock at 5-15 cm soil depth as compared to 0-5 cm soil depth were 34.24% in CT, 15.49% in PBB, 16.73% in PBB+R, 27.67% in PNB, 29.12% in PNB+R, 21.73% in ZT and 15.52% in ZT+R at the time of sowing, 27.69% in CT, 16.68% in PBB, 22.18% in PBB+R, 30.19% in PNB, 39.48% in PNB+R, 8.64% in ZT and 23.98% in ZT+R at the time of harvesting. In 30-45 cm soil depth CT had significantly lower carbon stock whereas ZT+R had significantly lower carbon stock at the time of sowing. A similar trend was observed at the time of harvesting. For total soil carbon stock in 0-45 cm soil depth CT had significantly lower and PBB+R had significantly higher with the magnitude of 36.97 and 47.14 Mg/ha at the time of sowing and for harvesting the carbon stock were 36.53 Mg/ha in CT and 46.01 Mg/ha in PBB+R. The average percentage of decrement in total carbon stock in harvesting as compared to sowing was 3.95%. The average carbon stock for all the treatments upto 45 cm soil depth was 43.54 Mg/ha at sowing and 41.88 Mg/ha at harvesting. Aggregate associated carbon is more in >2mm size aggregate irrespective of the treatments (Figure 4.10). In 0-5 cm soil depth the

aggregate associated carbon was more in PBB+R, similar trend was followed in 5-15, 15-30 cm soil depth, but minimum variation among the treatments in 30-45 cm depth.

Table 4.23: Total Organic Carbon stock (Mg/ha) of 0-5, 5-15, 15-30 and 30-45 cm soil depth at sowing and harvesting

Treatment	TOC Stock (Mg/ha)												Total stock Mg/ha	
	0-5 cm			5-15 cm			15-30 cm			30-45 cm			0-45 cm	
	Sowing	Harvesting		Sowing	Harvesting		Sowing	Harvesting		Sowing	Harvesting		Sowing	Harvesting
CT	5.45a	5.40a	10.30a	10.52a	13.83a	13.44a	7.08a	1.17a	36.97a	36.53a				
PBB	6.77b	6.90b	13.31ab	12.59ab	15.37ab	14.69ab	8.58ab	7.84ab	44.04bc	42.01bcd				
PBB+R	7.65b	7.69b	14.38b	13.57b	16.78b	16.58b	8.32ab	8.16ab	47.14c	46.01d				
PNB	6.57ab	6.52ab	12.02ab	11.37ab	15.34ab	14.80ab	7.71ab	8.37ab	41.66b	41.06bc				
PNB+R	6.79b	6.79b	13.23ab	11.53ab	17.08b	16.08b	7.82ab	7.99ab	44.94bc	42.4bcd				
ZT	6.63ab	6.7b	12.88ab	12.22ab	15.68ab	13.27a	8.26ab	7.79ab	43.44bc	39.98ab				
ZT+R	7.40b	7.3b	14.06b	12.94ab	16.24b	16.05b	8.87b	8.87b	46.57bc	45.17cd				

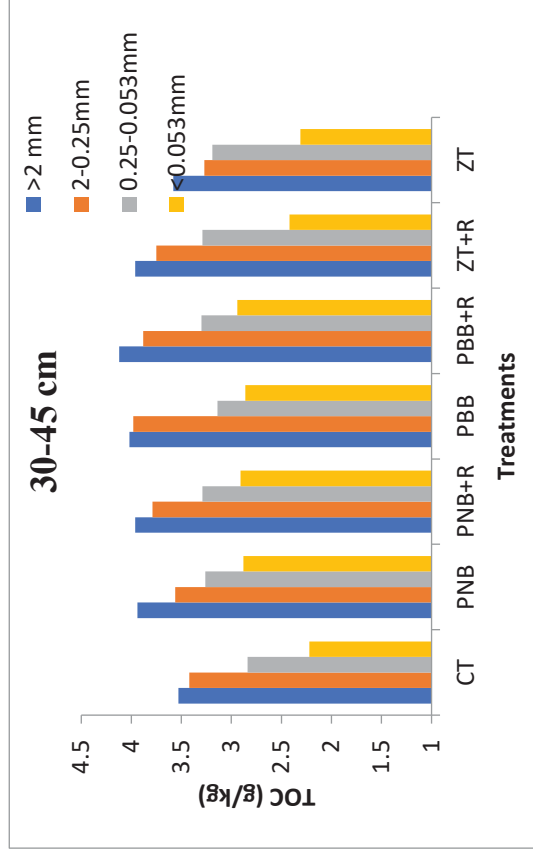
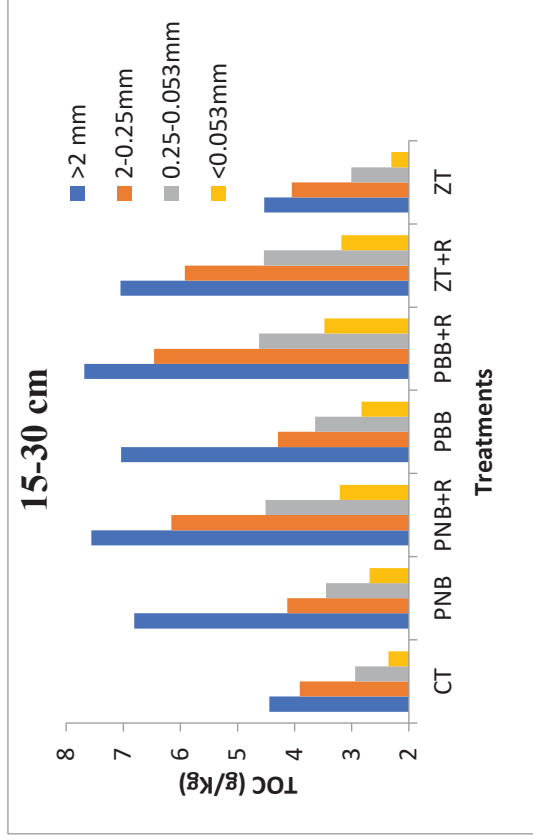
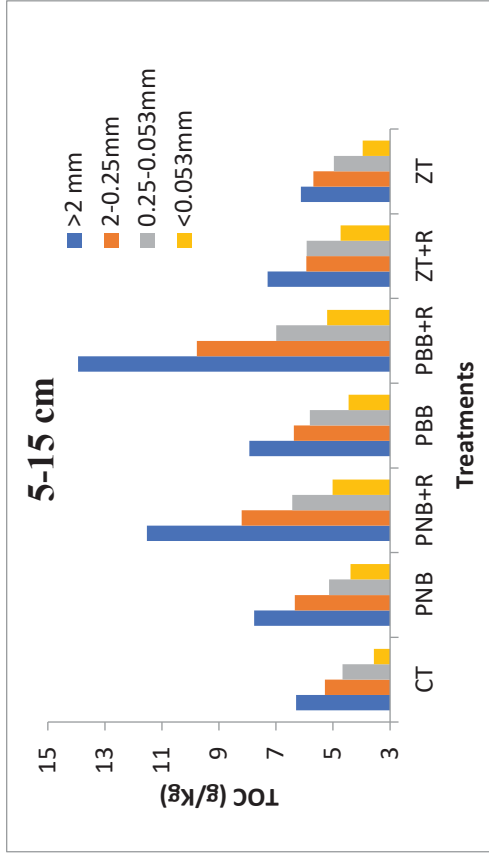
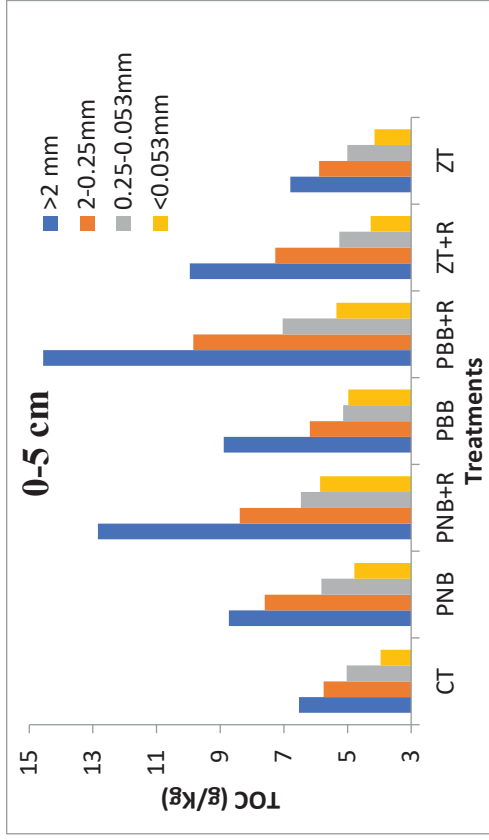


Figure 4.10: Aggregate associated carbon 0-5, 5-15, 15-30 and 30-45 cm soil depth

Table 4.24: Carbon pool (g/kg) of 0-5cm soil depth at sowing

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	1.79	0.97	2.02	2.76	2.76	4.70
PNB	1.97	1.34	1.70	3.93	3.31	5.63
PNB+R	2.2	1.44	1.82	4.11	3.64	5.93
PBB	2.06	1.41	1.78	4.12	3.47	5.90
PBB+R	2.54	1.66	2.10	4.74	4.19	6.84
ZT+R	2.24	1.42	2.14	4.37	3.66	6.51
ZT	1.8	1.29	1.80	3.68	3.08	5.48

Table 4.25: Carbon pool (g/kg) of 0-5cm soil depth at harvesting

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	1.73	1.01	1.95	2.53	2.74	4.48
PNB	2	1.31	1.65	3.74	3.31	5.39
PNB+R	2.13	1.39	1.76	3.98	3.52	5.74
PBB	2.09	1.36	1.73	3.91	3.46	5.64
PBB+R	2.44	1.69	2.01	4.45	4.13	6.46
ZT+R	2.12	1.29	2.49	3.32	3.41	5.80
ZT	1.89	1.15	2.22	2.96	3.04	5.18

Table 4.26: Carbon pool (g/kg) of 5-15 cm soil depth at sowing

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	1.13	0.73	2.59	2.19	1.86	4.29
PNB	1.76	1.12	2.16	2.96	2.88	5.12
PNB+R	2.10	1.28	2.37	3.38	3.38	5.75
PBB	2.02	1.14	2.38	3.26	3.17	5.63
PBB+R	2.16	1.38	2.65	3.63	3.54	6.29
ZT+R	1.83	1.22	2.36	3.32	3.54	5.68
ZT	1.48	1.09	2.26	2.96	3.06	5.22

Table 4.27: Carbon pool (g/kg) of 5-15cm soil depth at harvesting

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	1.16	0.71	2.51	2.06	1.9	4.57
PNB	1.64	1.04	1.93	2.82	2.7	4.76
PNB+R	1.75	1.11	2.06	3.01	2.9	5.08
PBB	1.80	1.14	2.12	3.10	2.9	5.23
PBB+R	2.05	1.31	2.43	3.55	3.4	5.97
ZT+R	1.5	1.11	2.06	3.25	2.6	5.31
ZT	1.34	1.19	1.86	3.05	2.5	4.91

Table 4.28: Carbon pool (g/kg) of 15-30 cm soil depth at sowing

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	0.57	0.63	2.06	2.46	1.2	4.52
PNB	0.70	0.82	2.09	2.72	1.52	4.81
PNB+R	0.79	0.93	2.36	3.07	1.72	5.43
PBB	0.70	0.83	2.11	2.75	1.53	4.85
PBB+R	0.82	0.97	2.46	3.21	1.79	5.67
ZT+R	0.61	0.81	2.16	3.18	1.42	5.34
ZT	0.55	0.73	1.95	2.87	1.28	4.82

Table 4.29: Carbon pool (g/kg) of 15-30cm soil depth at harvesting

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	0.59	0.54	2.37	1.94	1.13	4.30
PNB	0.61	0.79	2.06	2.61	1.40	4.67
PNB+R	0.67	0.87	2.21	2.95	1.54	5.17
PBB	0.59	0.71	2.02	2.61	1.31	4.63
PBB+R	0.69	0.90	2.36	2.99	1.60	5.35
ZT+R	0.52	0.85	2.08	3.06	1.37	4.14
ZT	0.42	0.68	1.67	2.46	1.10	4.13

Table 4.30: Carbon pool (g/kg) of 30-45cm soil depth at sowing

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	0.22	0.28	1.03	1.25	0.50	2.28
PNB	0.22	0.34	1.08	1.45	0.55	2.53
PNB+R	0.22	0.35	1.10	1.48	0.56	2.57
PBB	0.26	0.33	1.15	1.55	0.59	2.70
PBB+R	0.23	0.36	1.14	1.53	0.59	2.67
ZT+R	0.24	0.44	1.13	1.60	0.68	2.73
ZT	0.22	0.41	1.05	1.49	0.63	2.54

Table 4.31: Carbon pool (g/kg) of 30-45cm soil depth at harvesting

Treatments	Pool I (g/kg)	Pool II (g/kg)	Pool III (g/kg)	Pool IV (g/kg)	Labile Pool (g/kg)	Recalcitrant Pool (g/kg)
CT	0.25	0.30	1.25	1.02	0.55	2.27
PNB	0.26	0.33	1.18	1.50	0.59	2.68
PNB+R	0.25	0.32	1.14	1.46	0.57	2.60
PBB	0.21	0.33	1.09	1.42	0.55	2.51
PBB+R	0.26	0.32	1.15	1.47	0.58	2.62
ZT+R	0.24	0.44	1.12	1.63	0.68	2.75
ZT	0.21	0.39	0.98	1.42	0.59	2.40

The different pools soil organic carbon for all the treatments at different depths is given in the Table (4.24, 4.25, 4.26, 4.27, 4.28, 4.29, 4.30, 4.31). In 0-5 cm of soil depth, the average recalcitrant pool for all the treatments was 70.38 and 64.22% higher at sowing and harvesting as compared to labile pool. The average labile pool was higher in residue retention plot as compared to non-residue plot with the magnitude of 14.86% and 10.98% at sowing and harvesting respectively. The highest and lowest value of labile pool was observed in PBB+R with 4.19 g/kg and CT with 2.76 g/kg respectively, at the time of sowing. In 5-15 cm soil depth similar trend was followed. The decrease in labile pool in 5-15 cm depth as compared to 0-5 cm soil depth was as follows- 48.36% in CT, 14.76% in PNB, 7.57% in PNB+R, 9.39% in PBB, 18.55% in PBB+R, 19.74% in ZT+R and 19.89% in ZT at the time of sowing whereas at the time of harvesting the average decrement was 26.43% for all the treatments. In 15-30 cm soil depth the recalcitrant pool

was 70.56 and 71.82% higher in sowing and harvesting than labile pool. The average labile pool for all the treatment in 15-30cm soil depth was 1.49 g/kg at the time of sowing and 1.35 g/kg at the time of harvesting. In 30-45 cm soil depth a very less amount of labile pool was observed with an average of 0.59 g/kg for both sowing and harvesting.

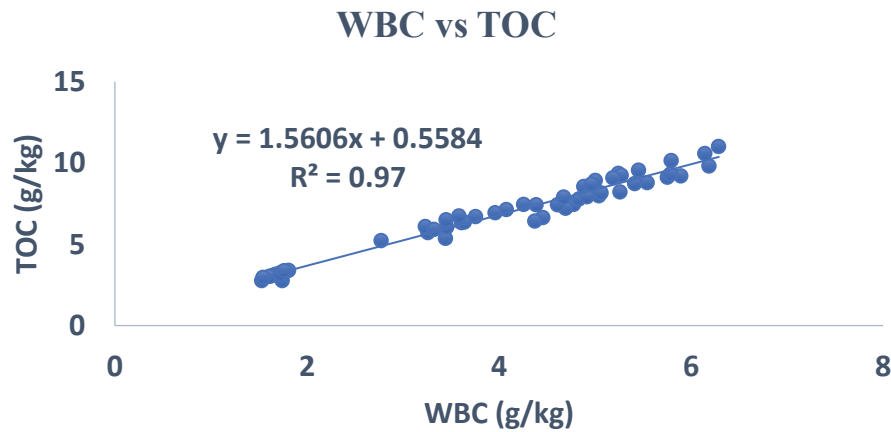


Figure 4.11: Relationship between TOC and WBC

The Figure 4.11 showed the linear relationship between TOC and Walkley and Black carbon with a R^2 value of 0.97

Labile carbon fractions of 0-5 cm soil depth (Pool I+ Pool II) for different treatments are given in (Table 4.24). Cumulative mineralization (C_m) was lowest under PNB followed by CT and the percent total SOC mineralized was 9.79 in 0-5 cm soil depth (Table 4.32). As compared to CT, all the CA plots had on an average 56.6 % more mineralization except PNB which had lower mineralization than all other plots. The highest C_m was obtained in PBB+R, though PBB had almost same C_m as in PBB+R. The residue applied plots had an average 21.93% more TOC mineralized as compared to non-residue applied plots. The mineralization constant (K_c) had highest value for PBB and lowest value was observed in PNB. In all CA plots there was 11.88% TOC mineralization which was 2.09 % more than CT.

Table 4.32: Labile carbon (C₀), Mineralized carbon (C_m) and decomposition constant (K_c) value at sowing in 0-5 cm soil depth

Treatments	Depth (0-5 cm)			
	C ₀ (mg/100 gm soil)	C _m (mg/100 gm soil)	K _c (x10 ⁻²)	% TOC mineralized
CT	276	73.13	1.21	9.79
PNB	331	77.18	1.01	8.64
PNB+R	364	109.33	1.34	11.43
PBB	347	133.65	1.84	14.27
PBB+R	419	135.85	1.47	12.31
ZT+R	366	127.25	1.62	12.52
ZT	308	103.87	1.57	12.13

In 5-15 cm of soil depth, lowest C_m value was obtained for CT and the trend followed as: PBB+R>PBB>PNB+R>ZT+R>PNB>ZT>CT (Table 4.33). After 28 days of incubation, the C_m in CT was 53.6 mg/100gm soil and average C_m value of 86.13 mg/100 gm of soil in all CA plots. Residue applied plots had 40.52 mg/100 gm soil more mineralization than non-residue plots. Lowest K_c value was obtained in PNB and highest K_c value was found in PBB. All CA plots had on an average 9.76 % more TOC mineralized which was 1.70 % more than CT. As the depth increases from 0-5 to 5-15 cm, the TOC % mineralized decreased by 1.73% whereas, in CA plots average decrease was 2.14%.

Table 4.33: Labile carbon (C₀), Mineralized carbon (C_m) and decomposition constant (K_c) value at sowing in 5-15 cm soil depth

Treatments	Depth (5-15)			
	C ₀ (mg/100 gm soil)	C _m (mg/100 gm soil)	K _c (x10 ⁻²)	% TOC mineralized
CT	186	53.6	1.32	8.06
PNB	288	59.67	0.89	7.45
PNB+R	338	94.79	1.22	10.37
PBB	317	108.31	1.55	12.30
PBB+R	354	110.13	1.38	11.21
ZT+R	306	88.76	1.29	10.16
ZT	257	55.11	0.91	7.07

In 15-30 cm of soil depth, lowest C_m value was obtained for CT and the trend followed as: $PBB+R > PBB > ZT+R > PNB+R > PNB > ZT > CT$ (Table 4.34). After 28 days of incubation, the C_m in CT was 24.67 mg/100gm soil and average C_m value of 42.63 mg/100 gm of soil in all CA plots. Residue applied plots had 33.44 mg/100 gm soil more mineralization than non-residue plots. Lowest K_c value was obtained in PNB and highest K_c value was found in PBB. All CA plots had on an average 6.17 % more TOC mineralized which was 1.86 % more than CT. As the depth increased from 0-5 to 15-30 cm, the TOC mineralized decreased by 5.48% in CT whereas, in CA practices plots average decrease was 5.7%.

Table 4.34: Labile carbon (C_0), Mineralized carbon (C_m) and decomposition constant (K_c) value at sowing in 15-30 cm soil depth

Treatments	Depth (15-30)			
	C_0 (mg/100 gm soil)	C_m (mg/100 gm soil)	K_c ($\times 10^{-2}$)	% TOC mineralized
CT	120	24.67	0.89	4.31
PNB	152	30.97	0.86	4.89
PNB+R	172	42.81	1.06	5.98
PBB	153	50.52	1.48	7.91
PBB+R	179	53.53	1.30	7.16
ZT+R	142	42.86	1.34	6.34
ZT	128	29.13	0.98	4.77

Table 4.35: Labile carbon (C_0), Mineralized carbon (C_m) and decomposition constant (K_c) value at sowing in 30-45 cm soil depth

Treatments	Depth (30-45)			
	C_0 (mg/100 gm soil)	C_m (mg/100 gm soil)	K_c ($\times 10^{-2}$)	% TOC mineralized
CT	50	15.07	1.41	5.41
PNB	55	20.37	1.77	6.61
PNB+R	56	25.15	2.26	8.01
PBB	59	29.22	2.57	8.86
PBB+R	59	33.24	3.10	10.19
ZT+R	68	23.92	1.65	7.00
ZT	63	18.02	1.29	5.68

In 30-45 cm soil depth the average Cm value for CA practices plots was 24.99 mg/100 gm which was 9.92 mg/100 g higher than CT. The average percentage of TOC mineralized was 7.72% in CA practices whereas in CT it was 5.41% i.e. 2.31% more than CT (Table 4.35). Cumulative SOC mineralization (Cm) started increasing from Day 3 onwards in 0-5 cm of soil layer (Figure 4.12, 4.13) for all the treatments and the peak Cm was obtained from 14 days after incubation in CT. Peak Cm was delayed in all CA based treatments. Under all CA practices treatments, peak Cm rate arrived 17 days after incubation. In 5-15 cm soil depth, the average Cm values were lower than the 0-5 cm soil layer. Cm started increasing 4-5 days after incubation. Arrival of peak Cm value was delayed by 3-4 days in CT and other CA practices treatments. Similarly, at 15-30 and 30-45 cm of soil depth, Cm values were lower irrespective of treatments.

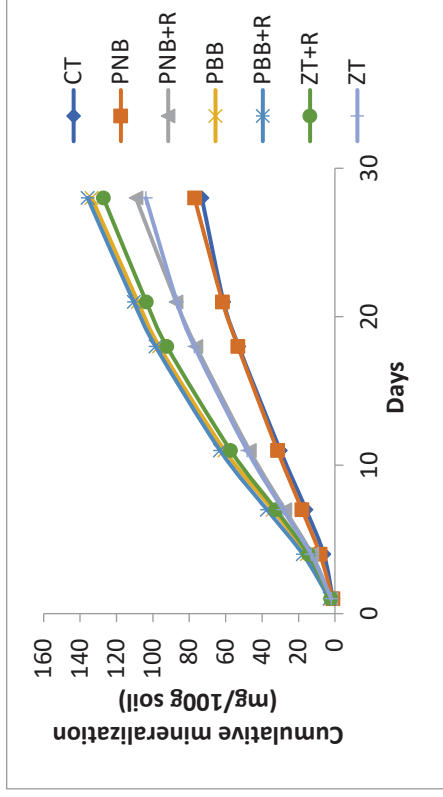


Figure 4.12: Cumulative carbon (C_m) mineralization of bulk soils as affected by different CA practices in the 0-5 cm and 5-15 cm soil layer at the time of sowing

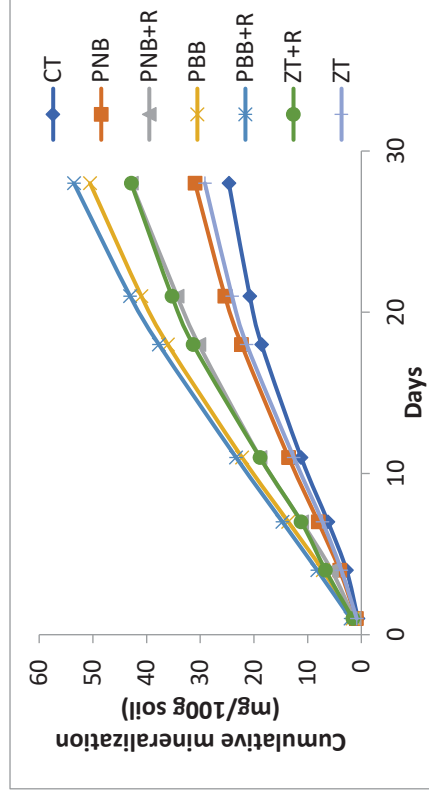
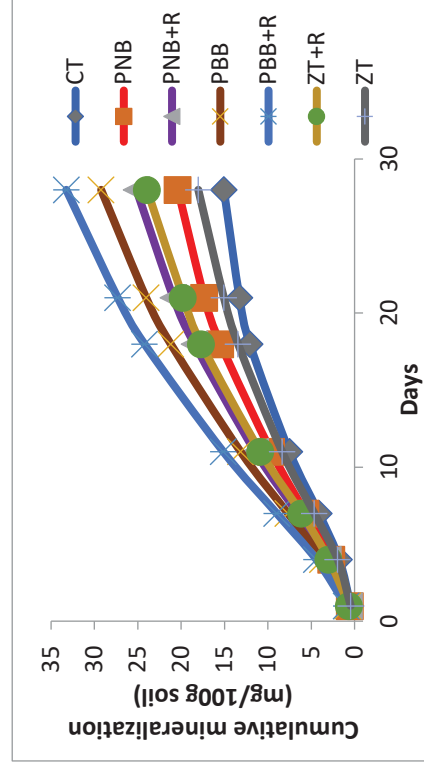
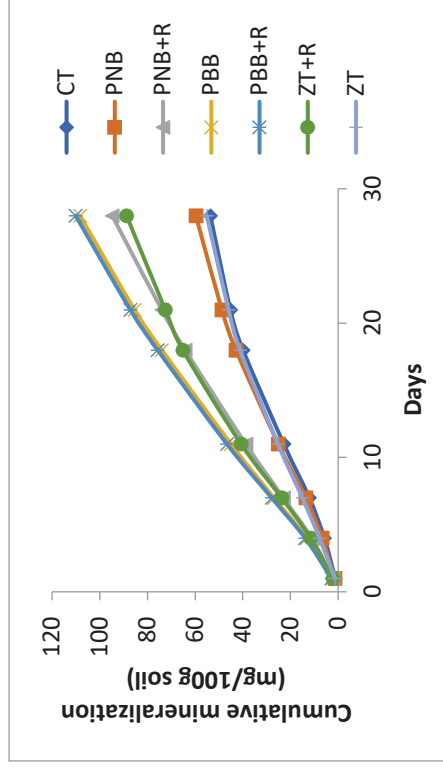


Figure 4.13: Cumulative carbon (C_m) mineralization of bulk soils as affected by different CA practices in the 15-30 cm and 30-45 cm soil layer at the time of sowing



4.3. Relationship of soil physical properties, porosity, pore size distribution and carbon mineralization

Figure 4.14 showed that mineralization is strongly influenced by porosity with a R^2 value of 0.74. Pearson correlation matrix among the mineralization, field observed porosity, X-ray computed tomography derived macroporosity, different classes of pores, soil structural stability (i.e. macroaggregates and MWD) and TOC have been given in Table 4.36. The data showed that mineralization rate is positively and strongly correlated with porosity, MWD, macroporosity and TOC. Mineralization is positively correlated with Class 1, 2 and 3 but negatively correlated with class 4 pores (though the relationship is not significant). The correlation between mineralization rate and class 2 is significant. Porosity is positively correlated with different classes of pores but the correlation is significant with class 2 pores. Macroporosity had negative correlation with class 1 pores, significant positive correlation with class 2 pores ($r=0.54$) and positively correlated with class 3 and 4 pores. Class 4 pores had negative correlation with MWD, macroporosity and TOC, though the relationship was not significant.

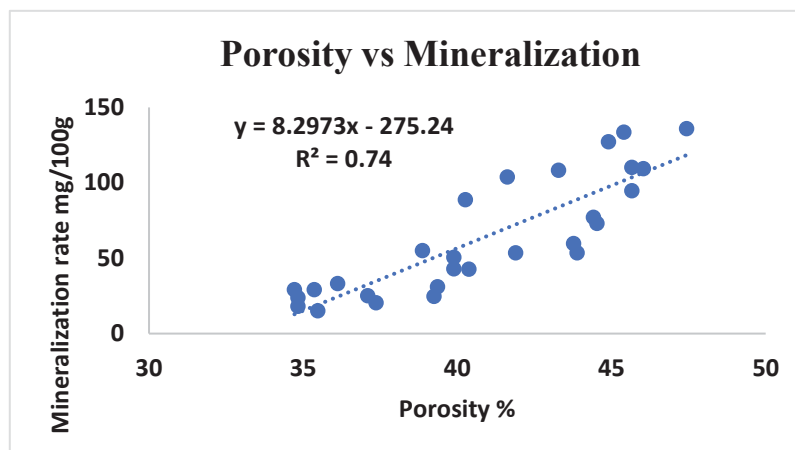


Figure 4.14: Effect of porosity on mineralization

Table 4.36: Correlation Matrix of mineralization and porosity, different classes pores and aggregation

Properties	Pearson Correlations Matrix									
	Mineralization	Porosity	Macroporosity	Class1 PN	Class2 PN	Class3 PN	Class4 PN	MWD	Macroaggragate	TOC
Mineralization	1									
Porosity	0.79**	1								
Macroporosity	0.59*	0.62*	1							
Class1PN	0.39	0.20	-0.04	1						
Class2PN	0.56*	0.58*	0.56*	0.26	1					
Class3PN	0.001	0.16	0.19	-0.05	0.59**	1				
Class4PN	-0.14	0.09	0.27	-0.21	0.50*	0.92**	1			
MWD	0.91**	0.85*	0.54*	0.33	0.65**	0.06	-0.09	1		
Macroaggragate	0.90**	0.82*	0.61**	0.24	0.60**	0.01	-0.14	0.95**	1	
TOC	0.90**	0.88*	0.56*	0.39	0.67**	0.05	-0.09	0.98**	0.92**	1

5. DISCUSSION

The results of previous chapter showed that there were significant changes in soil porosity, pore size distribution, bulk density, soil structural stability (i.e. mean weight diameter and macroaggregates), hydraulic conductivity, infiltration rate, organic carbon content and mineralization rate under CT and CA. Bulk density and hydraulic conductivity were strongly affected by soil structural stability. Carbon mineralization rate in soil was strongly dependent on porosity. Pore class of 110 to 500 μm size was found to be very effective and strongly influences carbon mineralization rates and other soil physical properties. Pore size of greater than 1500 μm found to have negative influence on soil properties. The findings of the above study have been discussed in the following sections:

5.1.1 Porosity and pore size distribution under CT and CA based treatments

In the current study, there was huge variation in number of soil pores among the treatments. In 0-5 cm of soil depth, total numbers of detected pores were highest in ZT+R, followed by PBB+R and lowest number of pores was found in PBB followed by ZT. As the depth increased, numbers of detected pores increased, smaller pores increased, macroporosity decreased irrespective of treatments. As the soil depth increased, the amount of undetected porosity increased in all the treatments. The numbers of detected pores in each class reduced as the pore diameter increased. Oseberg and McCoy (1992) observed increased porosity in CT as compared to no- tillage but numbers of effective pores or macropores reduced and continuity of pores was also less under ZT. Bhattacharyya et al. (2006) reported that tillage affected distribution of soil pores with time, and CA practices based treatments had more number of water-filled pores than CT plots because of better aggregate formation under CA based plots (Shukla *et al.*, 2003). Though ZT had higher BD and lower macroporosity, but it did not affect the water movement in the root zone (Bhattacharyya *et al.*, 2006) as more residue applied on these plots compensated. Hussain et al. (1998) observed that CT had more tillage-induced macropore in the surface soil layer but these were not properly connected to the deeper depth pores. Roseberg and McCoy (1992) observed increased porosity in CT which is in agreement with our study, but the macropores (effective pores) decreased in number, stability and continuity compared with no-till soil. Peth et al. (2008) studied aggregate

pore structure under CT and grassland area X-ray computed tomography, and observed noticeable differences in pore structure of the two aggregates of different treatments. In contrast to our study, CA system is associated with significant changes in soil porosity, particularly in the top soil as compared to CT treatments (Anikwe and Ubochi, 2007). Sasal et al. (2006) found 3.5% more porosity (obtained from BD and particle density) than ZT in 0-15 cm of soil layer. Mangalassery et al. (2014) observed bigger differences and 47% more X-ray computed tomography derived porosity with a system resolution of 64 μm . More number of macropores in CT as compared to CA based treatments in the top soil have been reported by many researchers (Bhattacharyya *et al.*, 2006) but a greater amount of micropores in CA treatments have been observed by Josa et al. (2013) and Mangalassery et al. (2014) which is in similar line with other study. Galdos et al. (2019) reported that the average macroporosity obtained from X-ray computed tomography 14.3% for the soil under CT which was similar to our study (15.71%) and they obtained around 19.7% macroporosity under CA based plots but in our study, we obtained lesser amount of macroporosity from X-ray computed tomography scan images which might be due to the presence of more numbers of micropores which our system was not able to capture. Galdos et al. (2019) reported highest pore volume under CT which is in the same line with our study but they observed a larger number of pores in CT than CA based treatments which differed from our results. In our study though the class 2 (110-500 μm) pores number was maximum under CT (which might be due to tillage practices and breakdown of soil aggregates (Bauer *et al.*, 2015)). but total numbers of detected pores were more in PBB+R, PNB+R and ZT+R. De Moraes et al. (2016) reported a greater macroporosity CT plots in the top 0-10 cm of soil layer as compared to long term CA treatments in Southern Brazil. They reported reduced amount of macroporosity beyond 10 cm of soil depth because of hard pan formation which is true for our study also where we observed higher BD value in subsurface soil layer. Lipiec et al. (2006) found greater areal and stained soil porosity in CT over long term ZT in a silt loam Eutric Fluvisol in Poland, using resin-impregnated soil blocks. Piccoli et al. (2017) observed no difference in macroporosity ($> 26 \mu\text{m}$) under CT and CA but ultramicroporosity (0.1–5 μm) increased in CA treatments as compared to CT. Under CA based treatments greater pore connectivity, reduced tortuosity and more amount of transmission could help better root

penetration and improved water and nutrient availability, gaseous exchange which might make clear the cause of high yield as reported by many authors all over the world (Pittelkow *et al.*, 2015; Das *et al.*, 2017a; Busari *et al.*, 2015).

5.1.2. Bulk density under CA

In our study, BD values of 0-5 and 5-15 cm of soil layer at the time of sowing showed that ZT had highest BD and lowest BD was observed in PBB+R followed by PNB+R (Table 4.13). The average increase in BD from sowing to harvesting was 5.05% with a range of 0.7-11.7% among all the treatments. In 15-30 cm soil, at sowing, there was not significant difference in BD among CT, PBB, PNB and ZT+R. BD was less in CT than ZT plot in surface soil layer. For different depths, the results showed that in general residue applied plot had lower BD as compared to non-residue applied plot. In 30-45 cm soil depth, average BD was 1.69 and 1.72 Mgm^{-3} for all the treatments at the time of sowing and harvesting, respectively. But no significant difference in BD was obtained among the treatments at the sowing and harvesting. Several studies by Gicheru *et al.* (2004), Gwenzi *et al.* (2009) and Enfors *et al.* (2011) conducted in Tanzania, Kenya, and Zimbabwe, separately observed that soil BD was not significantly different under CA and CT treatments within four to five years of CA adoption. Though, Osunbitan, *et al.* (2005) testified that after 8 yrs. of CA practices, soil BD in CA was significantly lower than CT. He *et al.* (2009) observed that BD of CA plot was higher for initial few years. So, it could be stated that the effect of CA on BD was not instant, it requires few years to lower the soil BD as compared to CT. No doubt, crop residues addition in CA plays an essential role in altering BD, since residue has less weight than mineral matter. As well as decomposition of crop residue released products which help in better aggregation (Acharya *et al.*, 2005; Shaver *et al.*, 2010). Increase in subsurface BD in CT may be due to more number of traffic passes in the course of tillage operations (MammanE. and Ohu, 1998). A greater BD and, higher soil strength in ZT had been reported by Martino and Shaykewich (1994) which can subsequently hinder root growth, encourage root branching and thereby cause reduced growth of the root main axes (Lampurlanes *et al.*, 2001). Tillage practices reduce BD and improved total and macroporosity in soil as compared to ZT (Bhattacharyya *et al.*, 2013). Chakrabarti *et al.* (2014) reported that a higher BD value (surface 15-30 cm soil depth) of 1.5 Mgm^{-3} under ZT plots in Karnal district of Haryana,

India. Aggarwal et al. (2006,) proved the superiority of bed planting in terms of reducing BD and mechanical impedance. Rai et al. (2019) and Shafeeq et al. (2020) also proved that BD under PBB+R is lowest because of improved porous environment bed planting system. Several researchers (Wu *et al.*, 1992, Bajpai and Tripathi, 2000) have showed higher BD under ZT at 0-15 cm and this might be due to non-disturbance of the soil matrix causing less total porosity as compared to CT plots.

5.1.3 Infiltration Characteristics under different CA practices

The infiltration study in our experiment showed that in the entire residue applied plots initial infiltration rate and steady state infiltration rates were higher. Cumulative infiltration of all the treatments followed the order: PBB+R>PNB+R>PBB>PNB>ZT>CT. Several researchers have reported that better soil structure and soil pore connectivity enable higher infiltration and eventually better available water for crop production (Aggarwal *et al.*, 2017; Shaxson, 2003; Thierfelder *et al.*, 2005) in different CA practices. Higher final IR in PBB+R was mostly because of more SOC content of soil due to residue retention and better aggregation (Bhattacharya *et al.*, 2015) and fairly more porous soil physical environment of soil profile (Aggarwal *et al.*, 2017; Rai *et al.*, 2017). From a two years study from Zambia and Zimbabwe, Thierfelder and Wall (2009) reported that infiltration was greater on residue protected undisturbed soils than on conventionally tilled and unprotected soils. Studies by Barzegar et al. (2002), Pansak et al. (2008), Fuentes et al. (2009) and Arachchi (2009) reported that soil moisture retention and infiltration capacity improves in CA due to more quantity of organic matter added through crop residue and greater number of pores as compared to CT in several parts of the world. Higher value of 'S' in residue applied plots was due to more porous environment and better soil structure than other treatments (Rai *et al.*, 2018). 'K' value of Phillip model is saturated hydraulic conductivity. Highest values of 'K' was obtained in PBB+R followed by PBB> PNB>PNB+R>CT which are almost similar to the experimentally observed values (data not shown). Model estimated 'K' value for ZT was found to be negative which indicated some unexplained error caused due to poor curve fitting of the model. From the results, it is clear that Kostiakov, Green Ampt and Philip models performed well for CT and five CA practices. But the negative value of 'K' obtained from the physical process-based Philip model shows the poor capability of statistical techniques in determining model coefficients. Similar inconsistencies in obtaining the model coefficients have been reported

by previous workers (Rai *et al.*, 2018; Shukla *et al.*, 2003; Kannan *et al.*, 2007). Several researchers have reported that better soil structure and soil pore connectivity enable higher infiltration and eventually better available water for crop production (Aggarwal *et al.*, 2017; Shaxson, 2003; Thierfelder *et al.*, 2005) in different CA practices. From a two years study from Zambia and Zimbabwe, Thierfelder and Wall (2009) reported that infiltration was greater on residue protected undisturbed soils than on conventionally tilled and unprotected soils.

5.1.4 Hydraulic conductivity under CA

In 0-15 cm of soil depth, highest saturated hydraulic conductivity (Ks) of 69.85 cm/day was obtained in PBB+R and lowest value of 55.30 cm/day was observed in ZT at the time of sowing. The Ks values decreased from 4.1 to 16.1 % as the crop progressed from sowing to harvesting. At 15-30 cm soil depth, though lowest Ks of 53.84 cm/day was obtained in ZT but it was not significantly different from CT. The trend of Ks was as follows: PBB+R>PNB+R>PNB>PBB>ZT+R>CT>ZT. The higher values in residue applied plots suggest that application of crop residues have improved soil drainage. The use of heavy machinery in tillage operations under CT caused substantial compaction of lower soil layers which in turn resulted in low saturated hydraulic conductivity (Mishra *et al.*, 2015). Saturated hydraulic conductivity is extremely dependent on soil porosity, BD, pore connectivity and distribution. In our study a higher value of Ks in CT as compared to ZT proved higher porosity as because in 0-30 cm soil depth BD in CT was lower than ZT. More Ks values in PNB and PBB treatments as compared to CT treatments were most likely because of less settling of soil particles on the bed surface, since irrigation water was not straightly applied to the bed surface (Aggarwal *et al.*, 2017). Irrigation of CT plots through flooding perhaps caused more settlement of the loose soil particles, thus, lowering of Ks. Also, in bed system (broad/narrow), lateral movement of water from furrows to beds resulted higher Ks (Aggarwal *et al.*, 2017). In our study, bed planting system (with or without residue) and ZT with residue retention caused lower sub-surface BD, increased Ks and higher infiltration rate. Results obtained in our study are in the same line with those of Govaerts *et al.* (2008) and Rai *et al.* (2017). They have reported PBB planting systems enhanced soil quality. Tullberg *et al.* (2007) and McHugh *et al.* (2009) also observed improved soil hydro-physical properties and more porous environment under PBB planting system. In the same way, Ghani *et al.* (2003) observed that

hydro-physical properties are greatly affected by different tillage methods (Lipiec *et al.*, 2009; Verhulst *et al.*, 2010; Shafeeq *et al.*, 2020). In our study, substantial reductions in BD, greater hydraulic conductivity and more cumulative infiltration under different CA practices confirmed greater soil structural/ aggregate stability under CA than CT. Similar results have been reported by Jin *et al.* (2007); Wang *et al.* (2009); Jat *et al.* (2011) and Eze *et al.* (2020). Few studies reported the insignificant changes in Ks in different tillage systems whereas studies by Obi and Nnabude (1988) and Celik (2011) revealed the negative impact of CA on Ks. McGarry *et al.* (2000) and Bhattacharyya *et al.* (2006) showed the increased values of HC in CA. Similar types of results have been reported by Sauer *et al.* (1990) and Karlen *et al.* (2003) under CA and CT. The increase in HC under CA might be due to better pore geometry like pore continuity (Cameira *et al.*, 2003), pore diameter (Sharratt, *et al.*, 2006) and large number of macropores. One of the reasons reported for improvement in hydraulic conductivity in no-tillage could be the characteristics of soil such as increase in the number of macropores (McGarry *et al.*, 2000).

5.1.5 Structural stability and aggregation under CA

In 0-5 cm soil depth, highest mean weight diameter (MWD) of 1.0 was obtained in PBB+R and lowest MWD of 0.82 was obtained in CT. The residue applied plots had 6.2% more MWD in sowing than non-residue applied plots. Although lowest MWD of 0.63 was observed in CT (15-30 cm soil depth), but significantly higher MWD were found in residue applied plots (i.e. PBB+R, PNB+R and ZT+R). The trend of MWD in 30-45 cm of soil depth followed the same trend as that in 15-30 cm soil depth. In 0-5 cm soil depth, lowest macroaggregates was found in CT and it was significantly lower than the other treatments at the time of sowing and PBB+R had highest macroaggregates of 54.92 g/100g soil. Residue applied plot had average 3.79 g/100g soil more macroaggregates than non-residue plots (i.e. ZT, PNB and PBB). Choudhary *et al.* (2019) reported that residue application increased the MWD and in 0–5 cm soil layer, MWD was maximum than the lower depth of the soil profile. Bhattacharyya *et al.* (2013) and Zotarelli *et al.* (2005) observed that the MWD of the aggregates was on average 0.5 mm higher under CA treatments as compared to CT in the 0–5 cm depth. Higher SOC content in 0-15 cm of soil layer under CA system might have caused more stable macroaggregates (Singh and Malhi, 2006). The more amount of soil organic carbon facilitates better aggregation

of soil particles (i.e. clay and silt fraction), thus improving the soil structure. The chemicals produced during decomposition process and root exudates encourage the clay and silt particles aggregation by temporary binding agents (i.e., fungal hyphae) and thus improve macro aggregation. Improved soil structure increases macroporosity in soil which further enhances the permeability of soil not merely for water, but for air and roots too (Tejada *et al.*, 2006). Whereas, in CT reduced aggregation is occurred because of physical destruction of soil through repeated tillage. Stability of microaggregates is more and these are less affected by soil management and tillage operations. Besides, they are accountable for maintaining long-term stability of soil organic carbon (Six *et al.*, 2004). In contrast, macroaggregates are prone to the soil use and management changes, and are particularly linked to the dynamics of the soil organic matter (Six *et al.*, 2004). The slaking of soil aggregates in CT is generally more than the system with higher inputs of organic matter, which leads to more microbial activity (Qin *et al.*, 2010). Similarly, to our results, Zotarelli *et al.* (2005) testified that the MWD of aggregates was on average 0.5 mm greater under CA than CT in the 0- 5-cm soil depth in Oxisols. ZT system generally increase SOC content and aggregate stability (Rhoton, 2000) and moderate soil hydrothermal regimes and improve water infiltration rates (Bhattacharyya *et al.*, 2006, 2008). Modak *et al.* (2019) reported that residue applied plots had 57% more macro-aggregates than the non-residue applied plots. Bhattacharyya *et al.* (2009) reported MWD and percent macroaggregates (>0.25 mm) under ZT was significantly higher than CT. More SOC in ZT, PBB, PNB along with residue retention may lead to more and stable aggregation in large macroaggregates (Lal *et al.*, 1994; Modak *et al.*, 2020). Mikha and Rice (2004) reported that X-ray computed tomography significantly decreased macroaggregates (>2.0 mm and 0.25–2 mm) with a associated increase in microaggregates (<0.25 mm) which is consistent with our findings. This may be attributed due to mechanical breakdown of macroaggregates in CT and exposure of SOC to degradation (Six *et al.*, 2000a; Ghosh *et al.*, 2016). In other CA treatments, the improvement in soil structural stability was due to higher earthworm activity and more microbial biomass than in CT (Bhattacharya, 2019). Residue retention in the soil encountered the destructive impacts of tillage on aggregation (Wright and Hons, 2005). Bhattacharyya *et al.* (2018) reported that in top 0-5 cm soil, micro-aggregates (0.25-0.053 mm) were the principal fraction accounting about~48 to

36% in soils in CT and PBB + R, respectively. They also reported that PBB + R plots had significantly greater proportion of large macro-aggregates (> 2 mm) as compared to CT plots in both 0–5 and 5–15 cm soil layers. Mechanical breakdown of macro-aggregates during tillage operations in CT might have reduced the size of large macro-aggregates (Six *et al.*, 2002; Bhattacharyya *et al.*, 2013a; Modak *et al.*, 2020). On the other hand, CA (ZT + R; PNB + R and PBB + R plots) improved macroaggregates formation, particularly in 0-15 cm soil depth. De Gryze *et al.* (2005) and Ghosh *et al.* (2016) also observed that addition of fresh organic material helps to build up hot spots for microbial activity which promotes new soil aggregates formation, thereby, causing more large macro-aggregates with residue application. As CA practices enhances SOC, improvement in aggregate stability is naturally observed (Blanco-Canqui and Ruis, 2018;). More fungal biomass and huge root networks in CA treatments has a positive effect (Wang *et al.*, 2010; Spurgeon *et al.*, 2013). A recent meta- analysis carried out world-wide showed that ZT with residue retention has 31% more macroaggregates than CT (Li *et al.*,2019b).

5.2 Effect of CA practices on carbon dynamics

With respect to CT, TOC was 47.6 % in PBB+R, 28.1% in PNB+R, 36.1% in ZT+R, 25.4 % in PBB, 19.5 % in PNB and 14.7% in ZT. TOC was reduced by 11.9% in CT, 6.48% in PBB, 12.21% in PBB+R, 11.63% in PNB, 4.82% in PNB+R, 9.87% in ZT and 16.49% in ZT+R in 5-15 cm soil as compared to 0-5 cm soil depth. On an average residue applied plots had 12.58-14.51 % more TOC in 0-30 cm soil depth at sowing and 9.21-17.39 % more at the time of harvesting. In 0-5 cm soil depth, the highest carbon stock was observed in PBB+R with a magnitude of 7.65 Mg/ha at the time of sowing which is significantly higher than CT. Higher TOC under PBB+R might be due to fresh organic matter addition leading to the formation of particulate organic matter (POM) and protection of SOC retained in intra-aggregates portion (Six *et al.*, 2000; Jat *et al.*, 2019; Bhattacharyya *et al.*, 2012). CA system, residues retained on the surface soil, cause slower decomposition of residue, and also protects the soil surface from destructive action of rain water and wind (Das *et al.*, 2013, Bhattacharyya *et al.*, 2009b, Bhattacharyya *et al.*, 2013), thus leading to more TOC in the soil. More TOC contents in the 0–5 and 5–15 cm layers of CA plots might have led to reduce the loss of SOC by gaseous emissions (Das *et al.*, 2013). Because of repeated use of heavy machinery in X-ray computed tomography system, there is

always rapid decomposition of organic matter, faster increase of profile soil temperature leading to less total SOC stock in CT (Das *et al.*, 2017b; Alvarez *et al.*, 2001, Bono *et al.*, 2008). When SOM is added to the soil in the form of residue or FYM, SOC increases with more values at the soil surface and then slowly reduces as depth increases (Ghosh *et al.*, 2016). Due to the availability of substrate the soil macro and micro fauna and flora are re-established in CA plots (Bhattacharya, 2019). Increased SOC to the extent of 3.6% to 6.1% in bed planting system along with residue retention has also been reported by Tripathi *et al.* (2015) which is similar to our findings. Schlesinger and Bernhardt (2013) stated that CT practices generally decrease soil organic matter, thereby thus dropping nutrient accessibility. Consistent with the current study, several workers reported that no-till system and cover cropping possibly will add organic matter to soil, thus improving physical structure (Tisdall and Oades, 1982), encourages biological activity (Varvel *et al.*, 2006), and increases the pool for C and nutrient cycling (Campbell *et al.*, 1996). Few workers have reported that SOC was unaltered by CA within four years of adoption as compared to CT (Biielders, *et al.*, 2002 and Moussa., *et al.*, 2010). On the other hand, in two distinct studies conducted by Nyamadzawo, *et al.*, (2008) and Gwenzi, *et al.*, (2009), observed that SOC was greater under CA after five and ten years of adoption. They explained that low SOC content in continuous cultivated soils of CT was due to less inputs of organic matter received through crop residues and repeated tillage encourages rapid organic matter oxidation. So, as per Nyamadzawo *et al.* (2008) and Gwenzi *et al.* (2009), SOC might alter after practicing CA for greater than four years. Tripathi *et al.* (2015) reported that in CA condition, residue retention with no nitrogen input improved OC content of soil up to 14.2% over without residue retention. In CA system, stubble of previous crop is left on the surface soil, indicating much lower stubble decomposition rate and thus, protecting of the soil surface from raindrop and wind action (Chivenge *et al.*, 2007). These factors are possibly very useful in achieving higher SOC content in 0-15 cm soil layer of CA plots. Reduced amount of tillage can decrease the amount of SOC lost by forming macroaggregates, thus providing the physical protection of particulate organic material (Page *et al.*, 2019). Several researchers have reported the linear increases in SOC stocks with increasing rates of residue addition (Duiker and Lal, 2016; Virto *et al.*, 2012; Liu *et al.*, 2014). Mohanty *et al.* (2015) reported that reduction in tillage along with residue

retention improved the total SOC by about 20% over CT in alluvial soils of India which is in agreement of our study.

In the present study, the average labile pool was higher in residue retention plot as compared to non-residue plot with the magnitude of 14.86% and 10.98% for sowing and harvesting respectively. Bhattacharya (2019) reported that in CA for 0-15 cm and 15-30 cm soil depth, labile pools were 36 and 22% more than CT and for both the soil layer, in CA plots recalcitrant pool was 12 and 9% more than CT. Campbell et al. (1996) stated that labile C pools are considered as soil health indicators since they are expected to be more prone to any changes in management practices as compared to total SOC. On the other hand, the recalcitrant pool is very gradually changed by microbial activities (Weil *et al.*, 2003) and plays a significant role in SOC retention and hereafter has been recognized as a probable indicator of better C retention under a set of management practices (Bhattacharyya *et al.*, 2012). Bhattacharyya et al. (2013) showed that plots under CA had around 33% more labile SOC (Pool II) than CT plots (2.01 g C kg⁻¹) in the 0- to 5-cm soil layer. Similar to our this study, Dou et al. (2008) observed that CA significantly ($P < 0.05$) improved SOC content. Jat et al. (2019) reported that higher labile SOC pool in CA because of greater biomass carbon. They also reported that PB+R had a higher concentration of labile SOC compared to that in permanent bed without residue. Jat et al. (2019) observed an increase of 10–23% in each pool of SOC under CA plots which is in agreement with our findings. Repeated tillage in CT breakdown down the soil aggregates and disrupts the soil microbial process (Bhattacharyya *et al.*, 2006), provides more access to the soil decomposer thus, decreases the recalcitrant CT as compared to ZT and ZT+R which is in line with our finding. Labile C pools are considered as soil health indicators due to their more sensitivity to agricultural management practices than total SOC (Campbell *et al.*, 1996; Bhattacharya, 2019). The recalcitrant C pool is very gradually changed by microbial activities (Weil *et al.*, 2003; Modak *et al.*, 2020) and helps considerably to SOC sequestration and therefore, has been considered as a potential sign of improved C accumulation (Bhattacharyya *et al.*, 2012).

5.3 Effect of porosity and pore size distribution and their relationship with other soil properties

5.3.1 Carbon mineralization under CA practices

As compared to CT, in 0-5 cm soil depth, all the CA plots had on an average 56.6 % more mineralization except PNB which had lower mineralization than all other plots. The entire residue applied plots had an average 21.93% more TOC mineralized as compared to non-residue applied plots. In our study, as the depth increased, the cumulative mineralization decreased and also the % TOC mineralized decreased. SOC mineralization is directly related to the amount of labile C pool present in the soil (Guo et al., 2019) which is reflected in our study. Grunwald et al. (2016) and Ribeiro et al. (2010) reported that addition of organic material in the soil accelerates the nutrient release process and significantly increases the mineralization of soil carbon pools. We have observed the same result in our study as the residue application causes more C mineralization. Garcia-Pausas and Paterson (2011) reported that SOC mineralization was strongly linked to the community composition and abundance of microorganisms which is further affected by the organic residue added to the soil (Bhattacharya, 2019).

Study conducted by Parihar et al. (2019) reported that CT plot had considerably lower C_m values during the incubation period than that of CA-based PBB and ZT plots which is in agreement with our findings. They have also reported that PBB had more C_m values all over the incubation period in 0-7.5 cm of soil depth which is in the same line of our study. Our findings differed from the findings of Balesdent et al. (1990) and Lamparter et al. (2009) who reported decreased SOC mineralization under CA plots as compared to CT. In our experiment, we received a higher K_c value in PBB than PBB+R which might be due to the better aggregation in residue applied plots thus protecting SOC as intra-particulate organic matter, therefore giving lower K_c values (Balesdent *et al.*, 1990; Lamparter *et al.*, 2009).

5.3.2 Relationship among carbon mineralization, porosity and pore size distribution, and other soil properties

In our study, we observed that mineralization rate is positively and strongly correlated with porosity, MWD, macroporosity and TOC. Mineralization is positively correlated with Class 1, 2 and 3 but negatively correlated with class 4 pores. Bouckaert et al. (2013)

reported a strong correlation between porosity and C mineralization. Like our study, Mtambanengwe et al. (2004) found a good correlation between labelled substrate C mineralization and clay content, bulk density and soil pore spaces. They have shown that pores with diameter $<75 \mu\text{m}$ is negatively correlated to C mineralization. In our study, pore diameter of 110 to 510 μm showed a positive significant correlation with C mineralization which has already proved by Bouckaert et al. (2013). Mtambanengwe et al. (2004) reported that pores of less than 75 μm are inaccessible for microbes and helps in carbon stabilization in soil. We found that class 4 pores having diameter $> 1500 \mu\text{m}$ has negative correlation with C mineralization which is in similar line with Strong et al. (2004) who reported that larger pores ($>300 \mu\text{m}$) to have a negative influence on SOM decomposition and recommended that larger pores could cause SOM protection rather than decomposition. Guo et al. (2019) reported a strong correlation among C mineralization, soil properties and soil microbial composition. Several researchers have reported that C mineralization is directly related to the amount of native SOC present in soil (Salomé *et al.*, 2010; Chen *et al.*, 2014a; Chen *et al.*, 2013) which is reflected in our study as the C mineralization increased with increase in SOC.

6. SUMMARY AND CONCLUSION

Porosity and pore size distribution has great impact on soil health as soil pore system affects soil physical properties, water and nutrient transport and gaseous exchange between the soil and atmosphere. On the other hand, maintaining soil organic carbon at optimum level has been a challenge for all agricultural scientists. Continuous tilling of land season after season has led to development of subsurface pan, and deterioration of soil structure because of loss of soil organic matter. All these have led to decrease in yields and crop production. A better alternative being recommended over the past few years is conservation agriculture (CA). CA practices help in improving the soil health parameters and increasing the sustainability of the agriculture system and better organic carbon in soil. At the time of decomposition, labile carbon is lost from the soil in the form of carbon dioxide. Soil pores have huge influence on C mineralization as pores affect substrate and moisture availability and also the soil pores provide habitat for soil microorganisms. In India quantification of porosity and pore size distribution in soil using 3D X-ray computed tomography has hardly been done. X- ray computed tomography allows for the visualization of pore structure at micron scale, but quantitative information on contribution of pores to the fate, protection and mineralization of soil carbon was still lacking. In the light of above, a research study was conducted with the following objectives:

- To quantify porosity and pore size distribution under conservation agriculture practices in maize -wheat rotation
- To study the effect of pore size distribution on carbon mineralization in soil

The study was conducted in long term experiment carried out since 2010 in Agricultural Research Farm (MB 14B) of ICAR- Indian Agricultural Research Institute. Soil samples were collected at the time of sowing (July) and harvesting (October) of maize crop from 0-5, 5-15, 15-30 and 30-45 cm of soil depths. There were seven treatments i.e. conventional tillage (CT), permanent narrow bed (PNB), PNB along with residue (PNB+R), permanent broad bed (PBB), PBB along with residue (PBB+R), zero tillage (ZT) and ZT along with residue (ZT+R). Porosity and pore size distribution were studied

using a X- ray computed tomography with a system resolution of 60 μm . Various properties such as total organic carbon (TOC), Walkley Black carbon (WBC), different pools of soil carbon, bulk density, soil aggregate classes, aggregate associated carbon, mean weight diameter (MWD), hydraulic conductivity (HC), infiltration rate were studied. To evaluate the effect of porosity and pore size distribution on soil carbon mineralization, incubation study was done for 28 days keeping the moisture content fixed at 60% of water filled pore space (WFPS). CO_2 samples were collected on day 1, 4, 8, 11, 18, 21 and 28 days. CO_2 samples were analyzed using a gas chromatography (GC). The salient findings of the study are summarized below:

- Based on the resolution of the instrument, pores were classified into four classes i.e. Class 1: 60-100 μm ; Class 2: 110-500 μm , Class 3: 510-1500 μm and Class 4: >1500 μm .
- Total numbers of detected pores in 0-5 cm of soil were highest in ZT+R, followed by PBB+R and lowest number of pores was found in PBB followed by ZT. In CT plots, the number of detected pores was increased 12.38% than ZT whereas, number of detected pores was higher by 88, 18.28 and 92.74 % in PBB+R, PNB+R and ZT+R, respectively.
- In class 2, residue applied plots had 60.40 % more pores than non-residue applied plots. Under CT, 197.12 % of more pores were found in class 3 than all CA based plots.
- Though the number of pores in class 1 was maximum in all the treatments except ZT and CT but their contribution to total detected pore volume was on an average only 0.27% for all the treatments. Volume contribution to the total detected volume was maximum from class 2 i.e. 110-1000 μm which was on an average 80.46% for all the treatments.
- In 5-15 cm soil layer, average numbers of pores in all CA based treatments were 153095 which was 3.67% more as compared to CT.
- Sphericity increased irrespective of treatments as the soil depth increased from 0-5 cm to 5-15 cm. Compactness also increased in all the treatments as the soil depth increased.

- In 5-15 cm of soil layer, average contribution of class 2 pores to total detected pore volume was around 90%.
- BD values of 0-5 cm of soil layer at the time of sowing showed that ZT had highest BD (1.55 Mgm^{-3}) and significantly different from CT and PBB+R. BD was lowest in PBB+R (1.39 Mgm^{-3}), followed by PNB+R (1.43 Mgm^{-3}). In PBB+R, BD was 8 and 15% lower than CT and ZT.
- In 5-15 cm soil depth, BD was lowest in PBB+R and PNB+R at sowing. Highest value of BD was obtained in ZT and it was 12.5% higher than PBB+R and PNB+R. CT had 7.1% higher BD than PBB+R and PNB+R.
- The findings of the current study are useful to understand the process of infiltration phenomena and to predict the infiltration rates under CT and different CA practices.
- The initial infiltration rate, steady state infiltration and cumulative infiltration were highest in the PBB+R plot. The time required to reach steady-state infiltration was also highest in PBB+R which shows that long term adoption of CA practices could improve the soil structure and distribution of soil water in the profile.
- After checking the model performance, it has been found that simple empirical Kostiakov (1932) infiltration model represented the infiltration rate and time relationship in a better way and characterized the best fit with the experimentally observed field infiltration data.
- In 0-15 cm of soil depth, highest saturated hydraulic conductivity (K_s) of 69.85 cm/day was obtained in PBB+R and lowest value of 55.30 cm/day was observed in ZT at the time of sowing.
- The K_s values decreased from 4.1 to 16.1 % as the crop progressed from sowing to harvesting.
- At 15-30 cm soil depth, though lowest K_s of 53.84 cm/day was obtained in ZT but it was not significantly different from CT which had a value of 55.60 cm/day at the time of sowing. PBB+R had significantly 20.8 and 24.7% than CT and ZT.

- The average decrease in Ks from sowing to harvesting was 2.34 %. Like surface layer (0-15 cm), Ks values were higher in residue applied plots during sowing and harvesting.
- In 0-5 cm soil depth, highest mean weight diameter (MWD) of 1.0 was obtained in PBB+R and lowest MWD of 0.82 was obtained in CT at the time of sowing.
- The residue applied plots had 6.2% more MWD at sowing than non residue applied plots, whereas, average MWD at the time of harvesting was 7.46 % more in residue applied plots.
- In 5-15 cm soil depth, average MWD of all treatments was 0.87 and 0.79 at the time of sowing and harvesting, respectively. CT had a range of 5.0- 14.6 % lower MWD than all other treatments.
- In 15-30 cm soil depth, residue applied plots had 3.76 % higher MWD than non-residue plots (i.e. ZT, PNB, PBB)
- There was 18.8 and 19.54 % reduction in MWD at sowing and harvesting as the soil depth increased from 15-30 to 30-45 cm.
- In 0-5 cm soil depth, lowest macroaggregates were found in CT and it was significantly lower than the other treatments at the time of sowing and PBB+R had highest macroaggregates of 54.92 g/100g soil. The average microaggregates content was 29.29 and 27.66 g/100g soil at sowing and harvesting in 0-5 cm soil depth.
- In 0-5 cm soil depth, the average TOC content of all the plots was 9.3 g/kg soil. CT had lowest TOC value of 7.50 g/kg at sowing and it was significantly lower than all other CA practices. PBB+R had significantly higher TOC than all other treatments.
- In 0-5 cm soil depth, the highest carbon stock was observed in PBB+R with a magnitude of 7.65 Mg/ha at the time of sowing which was significantly higher than CT. The percentage of increment in soil carbon stock compared to CT for all other treatments was 24.22% in PBB, 40.36% in PBB+R, 20.55% in PNB, 24.58% in PNB+R, 21.65% in ZT and 35.77% in ZT+R.
- In 0-5 cm soil depth the average recalcitrant pool for all the treatments was 70.38% at sowing and 64.22% at harvesting as compared to labile pool. The average labile

pool was higher in residue retention plot as compared to non-residue plot with the magnitude of 14.86% and 10.98% for sowing and harvesting respectively. The highest and lowest value of labile pool was observed in PBB+R with 4.19 g/kg and CT with 2.76 g/kg respectively at the time of sowing.

- There was linear relationship between TOC and Walkley and Black carbon with a R^2 value of 0.72.
- As compared to CT, all the CA plots had on an average 56.6 % more mineralization except PNB which had lower mineralization than all other plots in 0-5 cm soil depth
- In 5-15 cm of soil depth, lowest C_m value was obtained for CT and the trend followed as: PBB+R>PBB>PNB+R>ZT+R>PNB>ZT>CT.
- As the depth increased from 0-5 to 15-30 cm, the TOC % mineralized decreased by 5.48% in CT whereas, in CA plots average decrease was 5.7%.
- Mineralization rate is positively and strongly correlated with porosity, MWD, macroporosity and TOC.
- Porosity is positively correlated with different classes of pores but the correlation is significant with class 2 pores.
- Class 4 pores had negative correlation with MWD, macroporosity and TOC, though the relationship was not significant.

Conclusion:

From the above study, it can be concluded that X-ray computed tomography is a very effective tool in studying the porosity and pore size distribution of soils. In CA based treatments, there is improvement in porosity and pore size distribution which is reflected as better infiltration and hydraulic conductivity, reduced BD, improved MWD and macro aggregation, higher TOC and carbon stock upto 45 cm of soil depth. Though greater amount of labile carbon available in CA based treatments caused more carbon mineralization but recalcitrant organic carbon pool is also more in CA based treatments which indicates the ability of CA based treatments to increase SOC stock in soil. As the porosity and pore size distribution is positively related to carbon mineralization, CA

treatments had more mineralization. From our study, it can be concluded that pores > 1500 µm are not effective in carbon mineralization.

Future pathways:

From the experienced gained while accomplishing the objectives of the above study, following:

- In the present study, based on X- ray computed tomography images of soil samples, studies of wide range of soil properties and macro porous system was possible but the X- ray computed tomography analyses were restricted by the image resolution.
- As there is rapid development in tomography techniques, high resolution system is available, but characterization of mesopores and micropores are challenging.
- A lot of expertise on sample size, image contrast and processing are required.
- Also, soil sampling should be done at appropriate time from the field as intact X- ray computed tomography soil slice will give the best results.
- Second order kinetics model for C mineralization should be studied as it will give better understanding of the mineralization process in the soil.
- C mineralization study should be carried out along with the microbial population study in the field as the microbial habitat is affected by different classes of pores
- Also, the chemical composition of the pore water should be done at the time of C mineralization to get a better idea of SOC decomposition process in soil.
- As the present study was a first attempt to characterize porosity and pore size distribution using X-ray computed tomography, more research emphasis should be given to determine the different categories of pores and their influence on water, air and nutrient movement in soil profile because enhancing the input use efficiency is our prime goal.

Effect of porosity and pore size distribution on soil carbon mineralization under conservation agricultural practices

ABSTRACT

Porosity and pore size distribution of soils are greatly affected by agricultural management practices. At the same time porosity and pore size distribution affects the carbon mineralization in the soil. Soil pores have huge influence on C mineralization as pores affect substrate and moisture availability and also the soil pores provide habitat for soil microorganisms. So maintenance of optimum porosity in the soil is very important.

The study was conducted in long term experiment in progress since 2010 at the Agricultural Research Farm of ICAR- Indian Agricultural Research Institute. Porosity and pore size distribution were studied using a X-ray computed tomography with a system resolution of 60 μm . To evaluate the effect of porosity and pore size distribution on soil carbon mineralization, incubation study was done for 28 days keeping the moisture content fixed at 60% of water filled pore space (WFPS). CO_2 samples were collected on day 1, 4, 8, 11, 18, 21 and 28 days of incubation were analyzed using a gas chromatography. Based on the resolution of the instrument, pores were classified into four classes i.e. Class 1: 60-100 μm ; Class 2: 110-500 μm , Class 3: 510-1500 μm and Class 4: >1500 μm . Results showed that total numbers of detected pores in 0-5 cm of soil were highest in ZT+R, followed by PBB+R and lowest number of pores was found in PBB followed by ZT. In CT plots, the number of detected pores was higher by 12.38% higher than ZT whereas, number of detected pores was higher by 88, 18.28 and 92.74% in PBB+R, PNB+R and ZT+R, respectively. In class 2, residue applied plots had 60.40% more pores than non residue applied plots. Under CT, 197.12% more pores were found in class 3 than all CA based plots. Sphericity increased irrespective of treatments as the soil depth increased from 0-5 cm to 5-15 cm. Compactness also increased in all the treatments as the soil depth increased. In 5-15 cm of soil layer, average numbers of pores in all CA based treatments were 153095 which was 3.67% more as compared to CT. BD values of 0-5 cm of soil layer at the time of sowing showed that ZT had highest BD (1.55 Mg m^{-3}) which was significantly different than CT and

PBB+R. BD was lowest in PBB+R (1.39 Mg m^{-3}), followed by PNB+R (1.43 Mg m^{-3}). In PBB+R, BD was 8 and 15% lower than CT and ZT. In 0-5 cm soil depth, highest mean weight diameter (MWD) of 1.0 was obtained in PBB+R and lowest MWD of 0.82 was recorded in CT at the time of sowing. In 0-5 cm soil depth, the average TOC content of all the plots was 9.3 g/kg soil. CT had lowest TOC value of 7.50 g/kg at sowing and it was significantly lower than all other CA treatments. PBB+R had significantly higher TOC than all other treatments. As compared to CT, all the CA plots had on an average 56.6% more mineralization except PNB which had lower cumulative mineralization than all other plots. In 5-15 cm of soil depth, lowest C_m value was obtained for CT and the trend followed was: $PBB+R > PBB > PNB+R > ZT+R > PNB > ZT > CT$. As the depth increased from 0-5 to 15-30 cm, the TOC % mineralized decreased by 5.48% in CT whereas, in CA plots average decrease was 5.7%. Mineralization rate was positively and strongly correlated with porosity, MWD, macroporosity and TOC. Porosity was positively correlated with different classes of pores but the correlation is significant with class 2 pores. Class 4 pores had negative correlation with MWD, macroporosity and TOC, though the relationship was not significant. So, it can be concluded that CA practices are helpful to maintain better soil physical environment and improved porosity and pore size distribution in soil. As the present study was a first attempt to characterize porosity and pore size distribution using X-ray computed tomography, more research emphasis should be given to determine the different categories of pores and their influence on water, air and nutrient movement in soil profile because enhancing the input use efficiency is our prime goal.

Keywords: Conservation agriculture; porosity; pore size distribution; carbon mineralisation; X-ray computed tomography; permanent broad bed

संरक्षण कृषि प्रथाओं के तहत मृदा कार्बन खनिज पर सरंधता और छिद्र आकार वितरण का प्रभाव

सार

कृषि प्रबंधन प्रथाओं से मिट्टी के सरंधता और छिद्र आकार वितरण बहुत प्रभावित होते हैं। एक ही समय में सरंधता और छिद्र आकार वितरण मिट्टी में कार्बन खनिज को प्रभावित करता है। मृदा छिद्रों का कार्बन मिनरलाइज़ेशन पर बहुत अधिक प्रभाव होता है, क्योंकि छिद्र सबस्ट्रेट और नमी की उपलब्धता को प्रभावित करते हैं और मिट्टी के छिद्र मिट्टी के सूक्ष्मजीवों के लिए आवास प्रदान करते हैं। इसलिए मिट्टी में इष्टतम सरंधता का रखरखाव बहुत महत्वपूर्ण है। आईसीएआर-भारतीय कृषि अनुसंधान संस्थान के कृषि अनुसंधान फार्म में 2010 से चल रहे दीर्घकालिक प्रयोग में अध्ययन किया गया था। सरंधता और छिद्र आकार के वितरण का अध्ययन 60 माइक्रो मीटर के सिस्टम रिज़ॉल्यूशन के साथ एक्स-रे कंप्यूटेड टोमोग्राफी (माइक्रो सीटी) का उपयोग करके किया गया था। मृदा कार्बन खनिज पर पोरसिटी और छिद्र आकार के वितरण के प्रभाव का मूल्यांकन करने के लिए, ऊष्मायन अध्ययन 28 दिनों के लिए किया गया था, जिसमें नमी की मात्रा 60% पानी से भरे छिद्र स्थान (डब्ल्यूएफपीएस) को निर्धारित की गई थी। कार्बन डाइऑक्साइड नमूने दिन 1, 4, 8, 11, 18, 21 और 28 दिन में एकत्र किए गए थे, जिनका विश्लेषण एक गैस क्रोमैटोग्राफी का उपयोग करके किया गया था। साधन के संकल्प के आधार पर, छिद्रों को चार वर्गों में वर्गीकृत किया गया था अर्थात् वर्ग 1: 60-100 माइक्रोन; वर्ग 2: 110-500 माइक्रोन, वर्ग 3: 510-1500 माइक्रोन और वर्ग 4: >1500 माइक्रोन। परिणामों से पता चला कि 0-5 सेमी मिट्टी में कुल ज्ञात छिद्रों की कुल संख्या जेडटी आर में सर्वाधिक थी, इसके बाद पीबीबी आर और पीबी में सबसे कम संख्या और इसके बाद जेडटी में पाई गई। सीटी भूखंडों में, पता लगाए गए छिद्रों की संख्या जेडटी की तुलना में 12.38% अधिक थी, जबकि पता लगाए गए छिद्रों की संख्या क्रमशः पीबीबी आर, पीएनबी आर और जेडटी आर में 88, 18.28 और 92.74% अधिक थी। वर्ग 2 में, अवशिष्ट लागू भूखंडों में गैर-अवशेष लागू भूखंडों की तुलना में 60.40% अधिक छिद्र थे। सीटी के तहत, सभी सीए आधारित भूखंडों की तुलना में वर्ग 3 में 197.12% अधिक छिद्र पाए गए। मिट्टी की गहराई 0-5 सेमी से 5-15 सेमी तक बढ़ने के बावजूद गोलाई में वृद्धि हुई। मिट्टी की गहराई बढ़ने के साथ ही सभी उपचारों में कॉम्पैक्टनेस भी बढ़ गई। पीबीबी आर (1.39 एमजी एम⁻³) में बीडी सबसे कम था, इसके बाद पीएनबी आर (1.43 एमजी एम⁻³) था।

पीबीबी आर में, बीडी सीटी और जेडटी की तुलना में 8 और 15% कम था। 0-5 सेमी मिट्टी की गहराई में, 1.0 का उच्चतम माध्य भार व्यास (एमडबल्यूडी) पीबीबी आर में प्राप्त किया गया था और 0.82 का न्यूनतम एमडबल्यूडी बुवाई के समय सीटी में प्राप्त किया गया था। 0-5 सेमी मिट्टी की गहराई में, सभी भूखंडों की औसत टीओसी सामग्री 9.3 ग्राम / किग्रा मिट्टी थी। बुवाई के दौरान सीटी का टीओसी मूल्य सबसे कम 7.50 ग्राम / किलोग्राम था और यह अन्य सभी सीए उपचारों की तुलना में काफी कम था। पीबीबी आर में अन्य सभी उपचारों की तुलना में टीओसी काफी अधिक था। सीटी की तुलना में, सभी सीए प्लॉटों में पीएनबी को छोड़कर औसतन 56.6% अधिक खनिज था, जिसमें 0-5 सेमी मिट्टी की गहराई में अन्य सभी भूखंडों की तुलना में कम संचयी खनिज था। मिट्टी की गहराई के 5-15 सेमी में, सीटी के लिए सबसे कम सेमी मूल्य प्राप्त किया गया था और प्रवृत्ति इस प्रकार है: पीबीबी आर > पीबीबी > पीएनबी आर > आर > पीएनबी > जेडटी जेडटी > सीटी। जैसे-जैसे गहराई 0-5 से 15-30 सेमी तक बढ़ जाती है, टीओसी % खनिज में 5.48% की कमी हुई जबकि सीटी में, सीए भूखंडों में औसत कमी 5.7% थी। खनिज दर सकारात्मक रूप से और दृढ़ता से सहसंबंधी, पोरोसिटी, एमडबल्यूडी, मैक्रोपोरोसिटी और टीओसी के साथ संबंधित थी। पोरोसिटी को विभिन्न वर्गों के छिद्रों के साथ सकारात्मक रूप से संबद्ध किया गया था लेकिन सहसंबंध कक्षा 2 छिद्रों के साथ महत्वपूर्ण है। कक्षा 4 के छिद्रों का एमडबल्यूडी, मैक्रोपोरोसिटी और टीओसी के साथ नकारात्मक संबंध था, हालांकि यह संबंध महत्वपूर्ण नहीं था। तो, यह निष्कर्ष निकाला जा सकता है कि सीए प्रथा बेहतर मिट्टी के भौतिक वातावरण को बनाए रखने और मिट्टी में छिद्रों और छिद्रों के आकार में सुधार के लिए सहायक है। चूंकि हमारा अध्ययन *माइक्रो सीटी* का उपयोग करके छिद्र और छिद्र आकार के वितरण को चिह्नित करने का पहला प्रयास था, इसलिए छिद्रों की विभिन्न श्रेणियों और मिट्टी की प्रोफाइल में पानी, हवा और पोषक तत्वों के आंदोलन पर उनके प्रभाव को निर्धारित करने के लिए अधिक शोध पर जोर दिया जाना चाहिए क्योंकि इनपुट दक्षता को बढ़ाना हमारा मुख्य लक्ष्य है।

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