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Effect of Zero Tillage Practice on Physical Properties of Soil: A Review

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Abstract
Zero tillage (ZT), a core principle of conservation agriculture, minimizes soil disturbance and retains crop residues on the surface, offering a sustainable alternative to conventional tillage (CT). This review synthesizes research on the impact of ZT on key soil physical properties: bulk density, penetration resistance, hydraulic conductivity, infiltration rate, and moisture retention. Bulk density, a critical indicator of soil compaction and porosity, tends to be higher under ZT in initial years but decreases over time due to biological activity and residue-induced aggregation. Penetration resistance, which reflects mechanical impedance to root growth, may be elevated at the surface under ZT but is generally lower in deeper layers due to the absence of tillage-induced hardpans. Hydraulic conductivity and infiltration rate benefit from stable macropores and biopores preserved under ZT, enhancing water movement and reducing runoff. Surface residue cover also protects against slaking and sealing, improving infiltration efficiency. Moisture retention improves under ZT through reduced evaporation, increased soil organic carbon, and enhanced pore structure, leading to higher plant-available water. Field studies across diverse agro-ecosystems confirm that ZT supports better soil moisture dynamics and structural resilience. This review highlights ZT as a viable strategy for improving soil physical health and sustaining crop productivity under varying climatic conditions.

INTRODUCTION

Soil physical properties such as bulk density, penetration resistance, hydraulic conductivity, infiltration rate, and moisture retention form the cornerstone of productive and resilient agroecosystems. These attributes govern the availability and movement of water and air in the soil matrix, dictate root extension and nutrient uptake, and influence microbial activity—factors that collectively determine crop performance, especially under water-limited conditions (Doran, 1996; Strudley et al., 2008). In recent decades, degradation from intensive tillage, erosion, and declining organic matter has heightened the urgency to adopt practices that preserve soil structure, enhance water-use efficiency, and maintain long-term fertility. Conservation agriculture, with its three pillars of minimal soil disturbance, permanent soil cover, and diversified rotations, has emerged as a sustainable management paradigm. At the heart of this approach lies zero tillage (ZT), a practice that eliminates ploughing and relies on direct seeding into undisturbed, residue-covered soil. By maintaining existing pore networks and protecting surface mulch, ZT promises to mitigate the adverse effects of conventional tillage (CT) while fostering soil health and productivity.

Bulk density, defined as the mass of oven-dry soil per unit volume, serves as a primary indicator of soil compaction and porosity. Lower bulk density values generally correspond to greater total pore space, facilitating water infiltration, root proliferation, and gas exchange, whereas higher values reflect a compacted soil matrix that restricts these vital processes. In CT systems, mechanical disturbance initially fractures soil aggregates and reduces surface bulk density, but subsequent particle rearrangement and aggregate reconsolidation following rainfall or irrigation often reverse this benefit within weeks—surface bulk density can rebound by 55–61 percent in as little as eight weeks (Osunbitan et al., 2005). Zero tillage, by contrast, preserves existing aggregates and biopores, but may exhibit higher surface bulk density in the initial years due to the absence of mechanical loosening. Over time, however, the accumulation of crop residues, enhanced root proliferation, and earthworm activity under ZT foster macro-porosity and yield bulk density reductions that can surpass those achieved under CT in the upper horizon (Bogunovic et al., 2018; Yang et al., 2005).

Penetration resistance, measured by a cone penetrometer and expressed as the cone index, quantifies the mechanical impedance encountered by growing roots. A threshold cone index of approximately 2 MPa is widely accepted as the point beyond which root elongation is markedly hindered unless paths such as cracks or biopores are exploited (Bengough et al., 2011). Conventional tillage momentarily reduces resistance in the tilled layer, but repeated passes at a consistent depth contribute to the formation of compacted subsurface layers or "plough pans." Zero tillage, while preserving biogenic channels created by decayed roots and soil fauna, often shows higher surface penetration resistance during the early years of adoption as the soil lacks fresh mechanical loosening (Jabro et al., 2009; López-Fando et al., 2007). Seasonal fluctuations in soil moisture further modulate penetration resistance: wet soils exhibit reduced mechanical impedance, whereas drying rapidly increases cone index values irrespective of tillage history (Kukal & Aggarwal, 2003; Whalley et al., 2005).

Hydraulic conductivity and infiltration rate govern the movement of water into and through the pore network under saturated and unsaturated conditions. Saturated hydraulic conductivity represents the maximum water flux under gravity-driven flow, whereas unsaturated conductivity describes flow through partially filled pores under capillary tension. Both properties display pronounced spatial and temporal variability, influenced by aggregate stability, pore continuity, surface roughness, and residue cover (Reynolds et al., 2002; Coutadeur et al., 2002; Strudley et al., 2008). Conventional tillage can create a transient surge in conductivity by introducing new macropores, but mesopore collapse and increases in bulk density frequently reverse these gains within the growing season (Schwartz et al., 2003; Petersen et al., 2008). Zero tillage sustains stable macropore networks—often formed by undisturbed root channels and earthworm burrows—thereby maintaining higher conductivity and infiltration rates over multiple seasons (Wuest, 2001; Osunbitan et al., 2005). Residue retention under ZT further protects the soil surface from slaking and sealing, reducing runoff and enhancing water entry (Shaver et al., 2002; Kahlon et al., 2013).

Moisture retention in the root zone encompasses both the short-term control of evaporation and the long-term storage of plant-available water. Intensive inversion tillage exposes the soil surface, disrupts storage pores, accelerates evaporation, and often leads to lower volumetric water contents that compromise yield in water-limited environments (Kumar et al., 2013; Chan & Heenan, 2005). In contrast, zero tillage maintains a protective mulch layer that intercepts solar radiation, dampens soil temperature fluctuations, and curtails evaporative losses (Jalota et al., 2006; Van Wie et al., 2013). Over time, the decomposition of retained residues increases soil organic carbon—a key determinant of aggregate stability and pore structure—thereby enhancing the soil's water-holding capacity (Mosaddeghi et al., 2009; Lampurlanés et al., 2016). Minimum tillage practices have been shown to increase the abundance of mesopores, which are critical for retaining plant-available water, resulting in higher moisture content than CT systems (Pagliai et al., 2004; Alvarez & Steinbach, 2009).

Soil profile moisture dynamics under zero tillage have been documented across diverse agro-ecosystems. In the rice–wheat cropping system of Haryana, five years of comparative trials demonstrated that volumetric water content in the top 30 cm remained consistently higher under ZT than CT, supporting earlier root establishment and improved nutrient uptake (McVay et al., 2006). Similarly, participatory research in clay loam soils of North India revealed that minimum tillage combined with surface mulching increased topsoil moisture by 9 percent in rice–wheat and 3 percent in maize–wheat rotations relative to CT, highlighting the synergistic effect of reduced soil disturbance and residue management on moisture conservation (Bhatt & Khera, 2006).

Despite a growing consensus on the benefits of zero tillage, empirical studies present mixed and context-specific outcomes. Short-term increases in surface bulk density and penetration resistance under ZT often give way to long-term improvements in pore continuity and aggregate stability. Hydraulic conductivity gains in freshly tilled soils may be matched or exceeded by ZT's preservation of preferential flow paths. Moisture retention advantages of ZT peaks in water-scarce regions but can vary with soil texture and climatic regime. These depth-, time-, and site-dependent dynamics underscore the need to integrate soil type, residue management, traffic patterns, and seasonal water fluxes when evaluating tillage impacts.

This review synthesizes the extensive body of literature on zero tillage's influence on key soil physical properties—bulk density, penetration resistance, hydraulic conductivity and infiltration, and moisture dynamics—across contrasting soils and climates. By elucidating the mechanistic underpinnings and identifying the conditions under which ZT delivers the greatest benefits, we aim to inform adaptive management strategies, guide future research priorities, and support policy frameworks that promote resilient, productive soil systems

Effect of zero tillage on bulk density of soil:

Bulk density is widely recognized as one of the most fundamental physical properties of soil, serving as a critical indicator of soil health and functionality. It directly influences the soil moisture–air balance and root proliferation, thereby playing a pivotal role in determining crop growth and productivity. Its importance in soil quality assessment stems from its intrinsic relationship with other key soil attributes, including porosity, air permeability, penetration resistance, water retention, and hydraulic conductivity

(Doran, 1996). Moreover, bulk density is closely linked to soil compaction and is often used to evaluate the impacts of various agricultural management practices (Strudley et al., 2008).

Tillage practices exert a significant influence on soil bulk density, with conventional tillage (CT)—characterized by repeated mechanical disturbance—affecting soil structure differently than zero tillage (ZT), which minimizes soil disruption. Agricultural activities, coupled with natural events such as rainfall and irrigation during the crop growth cycle, induce dynamic changes in bulk density. Typically, the surface soil exhibits the lowest bulk density immediately following tillage, which gradually increases over time due to particle rearrangement and aggregate consolidation triggered by moisture events (Osunbitan et al., 2005). The surface layer is particularly susceptible to fluctuations in bulk density from sowing to harvest (Logsdon, 2012; Liu et al., 2014). Additionally, natural soil processes such as freeze–thaw cycles, swelling and shrinking, and erosion further contribute to variations in bulk density (Oztas and Fayetorbay, 2003; Hamza and Anderson, 2005; Logsdon, 2012).

Empirical studies examining the impact of zero tillage on bulk density have yielded mixed and sometimes contradictory findings. Certain investigations have reported higher bulk density under ZT compared to CT (Bhattacharyya et al., 2006a; Fuentesa et al., 2009), while others have observed a reduction in bulk density with ZT (Lafond et al., 1992; Ghuman and Sur, 2001). Some studies have found no significant difference between the two tillage systems (Goel and Verma, 1993; Ferreras et al., 2000). For instance, Grant and Lafond (1993) documented an increase in bulk density within the top 10 cm of a heavy clay soil under ZT relative to CT. Similarly, Dam et al. (2005), in a long-term study spanning 11 years of continuous corn cultivation on sandy loam soil in central Canada, reported consistently higher bulk density in the top 10 cm under ZT compared to reduced or conventional tillage. Another study highlighted that tillage effects were significant only in the 5–10 cm layer, where CT resulted in lower bulk density than direct drilling and reduced tillage, while deeper layers remained largely unaffected.

Yang et al. (2005), based on 16 years of rotational cropping with corn and soybean under ZT, found that bulk density was higher in the 5–20 cm layer under ZT than CT, whereas the reverse was true for the 30–40 cm depth. These findings underscore the complexity of bulk density dynamics, which are influenced by soil type, tillage history, residue management, and climatic conditions (Wander et al., 1998; Halvorson et al., 2000). Notably, ZT is often favored on clay soils due to its potential to reduce compaction and promote natural soil structure development.

The literature reveals two prevailing perspectives regarding the influence of tillage on bulk density. One school of thought suggests that ZT leads to increased bulk density relative to CT, while the other posits that ZT reduces bulk density over time. For example, Bogunovic et al. (2018) observed an 8% increase in bulk density in the 0–10 cm layer of sandy loam soil under ZT over four years, whereas CT exhibited a 6% higher bulk density at the 30–40 cm depth. Interestingly, by the seventh year, ZT recorded lower bulk density than CT in the surface layer, indicating that prolonged ZT may eventually reduce bulk density due to biological activity, root proliferation, and faunal contributions that enhance porosity in undisturbed soils. In contrast, CT often results in compaction at deeper layers due to the formation of a plough pan, a phenomenon attributed to repeated tillage at consistent depths (typically 10–15 cm), as reported by Aggarwal et al. (2006) and Ahmad et al. (2018).

Choudhary et al. (2018), through a participatory research trial in Karnal, Haryana on clay loam soils, found that after three years, bulk density in the 0–10 cm layer was 9% and 3% higher under CT than ZT in rice–wheat and maize–wheat systems, respectively. The rice–wheat system exhibited greater bulk density due to the puddling effect associated with rice cultivation (Gathala et al., 2011b). In contrast, Badagliacca et al. (2018) reported higher bulk density under ZT than CT after 20 years in a clay soil under wheat/wheat and faba bean/wheat rotations. Das et al. (2018) found no significant difference in bulk density between CT and ZT after three years across various cropping sequences in loam to sandy clay loam soils. A long-term experiment spanning 28 years revealed that ZT resulted in 7% lower bulk density than CT under continuous corn, corn–soybean, and corn–soybean–meadow rotations, which was attributed to greater residue retention on the soil surface. Soracco et al. (2012) similarly reported no discernible change in bulk density due to different tillage practices.

It is important to note that the timing of bulk density measurement can substantially affect the observed outcomes. Measurements taken immediately after tillage operations often yield artificially low bulk density values under CT compared to ZT. Osunbitan et al. (2005) documented a 55–61% increase in surface bulk density within eight weeks following tillage, highlighting the transient nature of tillage-induced changes in soil structure.

Effect of zero tillage on penetration resistance of soil:

Penetration resistance, commonly measured using a cone penetrometer, serves as a reliable proxy for assessing the mechanical resistance encountered by elongating plant roots within the soil profile. This parameter effectively simulates the physical constraints imposed by the soil on root growth and is particularly sensitive to compaction conditions, both at the surface and subsurface levels. Soil compaction, which manifests as mechanical impedance, restricts root proliferation into deeper horizons and consequently limits access to water and nutrients, thereby adversely affecting crop performance. Variations in penetration resistance are largely influenced by differences in soil management practices, tillage regimes, and moisture dynamics (Whitmore et al., 2011). A cone index value of 2 MPa is widely recognized as the threshold beyond which root elongation is significantly inhibited, unless the soil contains structural discontinuities such as cracks, biopores, decayed root channels, or fissures that roots can exploit to bypass compacted zones (Bengough et al., 2011).

Mechanical impedance is a globally prevalent issue that poses serious challenges to agricultural productivity. According to FAO (2015), approximately 4% of the global land area is affected by soil compaction, which often remains undetected due to its subsurface nature. This hidden compaction impairs the exchange of gases and water between the soil and growing roots, thereby disrupting essential physiological processes (McGarry and Sharp, 2003). The effects of compaction can be long-lasting or even permanent unless appropriate remedial measures are undertaken (Håkansson and Lipiec, 2000). Prolonged use of intensive tillage practices is a major contributor to subsurface compaction, particularly when operations are confined to a consistent depth. The severity of compaction is further influenced by initial soil conditions such as texture, moisture content, bulk density, and aggregate stability (Imhoff et al., 2004; Horn et al., 2005; Materechera, 2009). Soils with low organic matter content are especially vulnerable, as they lack the structural resilience needed to resist compressive forces (FAO, 2015).

Penetration resistance is governed by the interplay between mechanical impedance and soil water matric potential. It varies significantly with soil moisture levels, as even compacted soils may exhibit reduced resistance under high moisture conditions due to the lubricating effect of water (Kukal and Aggarwal, 2003). Conversely, as soils dry, their strength increases rapidly, exacerbating mechanical constraints on root growth (Whalley et al., 2005; Whitmore and Whalley, 2009). A survey involving 19 soils with textures ranging from loamy sand to silty clay loam revealed that 10% and 50% of the samples exceeded the critical 2 MPa threshold at matric potentials of −10 and −200 kPa, respectively, underscoring the widespread nature of compaction-induced limitations (Bengough et al., 2011). In field conditions, soil moisture fluctuates continuously due to irrigation, rainfall, drainage, and evapotranspiration, leading to dynamic changes in both mechanical impedance and water availability (Veen and Boone, 1990; Bengough et al., 2011). In rice-wheat cropping systems prevalent in South Asia, puddling during rice cultivation has been extensively documented to degrade soil aggregates and promote the formation of compact subsurface layers (Aggarwal et al., 2006; Kumar et al., 2014a; Kukal and Aggarwal, 2003; Singh et al., 2014). The retention of crop residues on the soil surface has been shown to mitigate surface compaction by cushioning the impact of machinery and rainfall, thereby preserving aggregate structure (Thomas et al., 1995).

Long-term evaluations of penetration resistance under different tillage systems have provided valuable insights into the structural evolution of soils. Jabro et al. (2009), in a study spanning over 20 years of continuous spring wheat cultivation, reported significantly higher penetration resistance under zero tillage (ZT) up to a depth of 10–15 cm, followed by a decline in deeper layers. Similarly, López-Fando et al. (2007) observed soil strength values reaching up to 3 MPa at 150 cm depth in ZT plots in central Spain. Sub-soiling under zone tillage demonstrated an immediate and substantial reduction in cone index values up to 30 cm depth, although differences beyond 40 cm were negligible. Bogunovic et al. (2018) found that penetration resistance was higher under ZT than conventional tillage (CT) during the seeding phase up to 30 cm depth, but this trend reversed during flowering, indicating temporal shifts in soil strength. Other studies have reported that initial differences in soil impedance between CT and ZT diminish over the growing season, suggesting that CT soils are prone to rapid re-compaction (Yavuzcan et al., 2005). Interestingly, Fabrizzi et al. (2005) noted that moderate compaction in sandy soils could enhance water retention and root growth, indicating that the effects of compaction are context-dependent.

Soil compaction impairs subsoil functionality by restricting root penetration and limiting water and gas exchange (McGarry and Sharp, 2003). It reduces macro-porosity, impedes nutrient mobility, and ultimately suppresses crop yields (Sidhu and Duiker, 2006; Drewry et al., 2008). In the Indo-Gangetic Plains of Indian Punjab, Kukal and Aggarwal (2003) reported a 50–68% reduction in root biomass in highly puddled soils, underscoring the severity of compaction in rice-based systems. The adoption of conservation tillage practices, which aim to minimize soil disturbance and enhance structural stability, offers a promising avenue for mitigating compaction and sustaining productivity in rice-wheat systems (Hobbs et al., 2008).

Aggarwal et al. (2006) employed multiple regression analysis to model penetration resistance as a function of bulk density, soil moisture, and depth. Their findings revealed that soil water content alone accounted for 59% of the variation in resistance, while the combined influence of moisture and bulk density explained up to 96% of the variability in sandy clay loam soils of the western Indo-Gangetic Plains. These insights reinforce the need for integrated soil management strategies that consider both physical and hydrological parameters to optimize root growth and crop performance

Effect of zero tillage on Hydraulic conductivity and infiltration rate of soil:

Hydraulic conductivity, particularly under saturated conditions, is regarded as one of the most critical soil physical parameters governing water movement and solute transport within the soil matrix. It plays a central role in regulating infiltration, drainage, and chemical leaching processes, thereby influencing both agronomic performance and environmental outcomes (Reynolds et al., 2002). Among the various soil properties, bulk density and effective porosity are frequently measured indicators that directly affect hydraulic conductivity (Strudley et al., 2008; Jabro et al., 2009). Both saturated and unsaturated hydraulic conductivity are inherently variable across spatial and temporal scales, influenced by soil texture, structure, moisture status, and biological activity (Coutadeur et al., 2002). Unsaturated hydraulic conductivity, in particular, is highly sensitive to soil water content and can fluctuate significantly even with minor changes in moisture levels (Strudley et al., 2008).

Tillage practices exert a substantial influence on soil hydraulic behavior by modifying surface roughness, aggregate stability, pore geometry, and the distribution of crop residues. These alterations affect the continuity and connectivity of soil pores, which are fundamental to water transmission. While bulk density and porosity are commonly used to assess tillage-induced changes, a more nuanced understanding of pore architecture—especially the geometry and continuity of macro- and meso-pores—is essential for accurately interpreting the effects of tillage on hydraulic properties (Kutilek, 2004). Although increased total porosity may suggest improved infiltration, this is not always the case if the continuity of larger pores is disrupted. The impact of tillage on infiltration and conductivity is highly variable, depending on the type, depth, and duration of tillage operations. Typically, tillage enhances soil openness to water and air in the short term, but this benefit diminishes over time due to reconsolidation and compaction. Several studies have reported that hydraulic conductivity improves immediately after tillage but declines progressively during the cropping season, primarily due to increased bulk density and the collapse of conductive meso-pores (Schwartz et al., 2003; Bormann and Klaassen, 2008; Petersen et al., 2008; Mellis et al., 1996; Messing and Jarvis, 1993).

Strudley et al. (2008) emphasized the need for targeted studies examining the influence of irrigation and rainfall on the hydraulic properties of recently tilled soils. Busari and Salako (2012) observed higher infiltration rates and unsaturated hydraulic parameters under conventional tillage (CT) compared to zero tillage (ZT) at the end of the first year, although this trend reversed in the second year. The initial advantage in CT was attributed to the presence of fast-draining macro-pores, which diminished over time due to particle settling and pore blockage (Martínez et al., 2008; Pikul and Aase, 2003; Shukla et al., 2003a). Long-term adoption of reduced tillage has been shown to enhance infiltration, possibly due to increased biological activity, particularly earthworm populations, which contribute to biopore formation. Wuest (2001) reported significantly higher ponded infiltration rates and earthworm populations under ZT systems. The biogenic channels formed by earthworms and decayed roots remain largely undisturbed under ZT, facilitating higher hydraulic conductivity even in soils with elevated bulk density (Osunbitan et al., 2005).

Zero tillage combined with surface residue retention has demonstrated potential to improve water infiltration, reduce erosion, and enhance water use efficiency relative to conventional tillage (Shaver et al., 2002; Johnston and Bailey, 2002). Das et al. (2018) recorded higher infiltration rates under conservation tillage, except during the initial growth stage when CT soils exhibited drier surfaces. Over time, slaked particles in CT systems led to pore blockage and surface sealing, reducing infiltration efficiency (Kahlon et al., 2013). Residue cover mitigates the kinetic energy of raindrops and irrigation water, thereby reducing the risk of slaking and surface sealing. As residues decompose, they contribute to soil organic carbon (SOC) accumulation, which promotes aggregate formation and stability, further enhancing pore structure and water entry.

Nyamadzawo et al. (2007) documented superior infiltration under fallow conditions compared to continuous maize cultivation, attributing the improvement to the restoration of soil physical properties during fallowing. Enhanced pore connectivity, the presence of decayed root channels, vertical cracks, and earthworm burrows have been shown to significantly alter soil hydraulic behavior (Alvarez and Steinbach, 2009; Mupangwa et al., 2013; Huang et al., 2015a; Busari et al., 2015; Castellanos-Navarrete et al., 2012). Even in soils with relatively low total porosity, the continuity of macro- and meso-pores can substantially improve infiltration rates (Nielsen et al., 2005). The role of macro-pores in facilitating rapid infiltration under ponded conditions—often referred to as preferential flow—has been well documented (Guerif et al., 2001; Beven and Germann, 2013). Lin et al. (1996) reported that approximately 10% of macro-pores (>0.5 mm) and meso-pores (0.06–0.5 mm) accounted for nearly 89% of total water flux in soil profiles.

The adoption of reduced tillage has consistently been associated with improvements in hydraulic conductivity and infiltration rates, largely due to enhanced biological activity and the preservation of surface-connected macro-pores (Horn and Smucker, 2005; Bhattacharyya et al., 2006a; Alvarez and Steinbach, 2009; Parvin et al., 2014). McGarry et al. (2000) observed increased hydraulic conductivity and infiltration under ZT compared to CT in alluvial soils of the semi-arid subtropics. However, the effects of ZT are not universally consistent. Some studies have reported similar (Ankeny et al., 1990) or even lower infiltration rates under ZT compared to CT (Gómez et al., 1999; Rasmussen, 1999). Sasal et al. (2005) found no significant improvement in infiltration under ZT, despite a 30% increase in aggregate stability. Kumar et al. (2000) observed higher basic water intake under CT in clay loam soils of Haryana, suggesting that soil texture and initial structure play a decisive role in determining tillage outcomes. Bodner et al. (2008) investigated the influence of cover crop canopy and residue coverage on hydraulic properties and found that vegetative cover significantly enhanced conductivity compared to bare soils, while continuous cultivation led to a decline in hydraulic conductivity even within the root zone.

Bhattacharyya et al. (2006a) reported a marked increase in hydraulic conductivity under ZT following rice cultivation in a rice-wheat system. This improvement was attributed to enhanced porosity, favorable pore size distribution, and increased root biomass and residue retention. The maintenance of pore continuity, facilitated by stable aggregates and favorable pore geometry, was further supported by heightened biological activity, including soil fauna that contribute to biopore formation and structural resilience

Effect of zero tillage on soil moisture retention:

The practice of intensive tillage has long been associated with adverse impacts on soil physical properties, particularly in relation to water and nutrient availability. Repeated mechanical disturbance of the soil disrupts its structure, reduces organic matter content, and accelerates moisture loss, ultimately leading to a decline in crop yields (Kumar et al., 2013; Hou et al., 2012; Chan and Heenan, 2005). One of the key contributors to this moisture depletion is the removal or incorporation of crop residues during tillage operations, which leaves the soil surface exposed and devoid of protective mulch, thereby intensifying evaporation losses.

In contrast, conservation tillage systems—defined by maintaining a minimum of 30% surface coverage with crop residues or cover crops—have gained prominence as effective strategies for soil and water conservation (Corsi et al., 2012). Among these, zero tillage (ZT) has emerged as a particularly promising approach for enhancing in-situ moisture retention, especially in arid and semi-arid regions where water scarcity poses a significant constraint to agricultural productivity (Ngigi et al., 2006). By minimizing soil disturbance and preserving surface residues, ZT creates a favorable hydro-thermal environment that supports optimal root development and sustains crop growth under moisture-limited conditions.

Surface-retained crop residues play a crucial role in intercepting solar radiation, thereby reducing soil temperature and evaporation rates (Jalota et al., 2006; Salado-Navarro and Sinclair, 2009; Regina and Alakukku, 2010; Van Wie et al., 2013). This residue-mediated insulation effect contributes to improved soil moisture conservation (Alletto et al., 2011; Mondal et al., 2018b). However, it is worth noting that some studies have reported elevated evapotranspiration under ZT, possibly due to increased canopy cover and transpiration demand (Su et al., 2007). Nonetheless, the overall impact of ZT on soil moisture retention remains positive, largely due to its influence on soil pore architecture. No-tillage and minimum tillage practices have been shown to increase the number of storage pores—particularly meso-pores—which enhance the retention of plant-available water (Pagliai et al., 2004; Bhattacharya et al., 2006a; Mondal et al., 2013). These structural improvements contribute to higher water availability compared to conventional tillage systems (McVay et al., 2006; Kargas et al., 2012; Alvarez and Steinbach, 2009).

The enhancement of soil organic carbon (SOC) under conservation tillage further amplifies moisture retention capacity. Increased SOC improves soil aggregation, porosity, and water-holding potential, thereby creating a more resilient soil system (Murphy, 2015; Mosaddeghi et al., 2009; Lampurlanés et al., 2016). However, Rawls et al. (2003) cautioned that the effect of SOC on water retention may vary depending on soil texture and initial carbon levels, indicating the need for site-specific assessments.

Zero tillage also contributes to reduced surface runoff by preventing the slaking of soil aggregates and the formation of surface seals. The protective mulch layer formed by crop residues absorbs the kinetic energy of raindrops, thereby preserving soil structure and enhancing infiltration. Numerous studies have demonstrated the efficacy of ZT in increasing soil moisture storage and retention (Moret and Arrue, 2007; Schwen et al., 2011; Castellini and Ventrella, 2012). Hangen et al. (2002) reported that conservation tillage on silty soils significantly improved water retention by minimizing runoff. Bhattacharyya et al. (2006a) quantified the benefits of ZT in terms of plant-available water capacity, noting values of 5.07 cm and 4.86 cm after rice and wheat crops, respectively, compared to 4.23 cm and 4.21 cm under conventional tillage in the top 30 cm of soil.

The soil water characteristic curve, which describes the relationship between soil water content and matric potential, is influenced by several factors including soil structure, texture, and compaction (Vanapalli et al., 1999; Zhou and Yu, 2005). Under ZT, the preservation of surface residues and minimal soil disturbance contribute to improved moisture retention by maintaining favorable pore connectivity and reducing evaporative losses (Moreno et al., 2001; Boydaş and Turgut, 2007; Zhang et al., 2007). McGarry et al. (2000) reported a 28% increase in plant-available water at sowing under ZT compared to CT. Similarly, soil water storage was found to be 25% higher under ZT, with significant improvements in plant-available water in rice-wheat cropping systems (Bhattacharyya et al., 2006b; Su et al., 2007; Bhattacharyya et al., 2008). Sharma et al. (2015) observed a 12.4% increase in soil moisture during maize and a 16.6% increase during wheat under minimum tillage relative to conventional tillage in a maize-wheat rotation system.

These findings collectively underscore the potential of zero tillage as a sustainable soil management practice that enhances moisture retention, improves water use efficiency, and supports resilient crop production under varying agro-climatic conditions.

Effect of zero tillage on Soil profile moisture:

Long-term field experimentation conducted over a five-year period in the rice–wheat cropping system of Haryana has provided compelling evidence that zero tillage significantly enhances soil profile moisture, particularly in the upper layers of the soil. The comparative analysis between zero tillage and conventional tillage systems revealed that the former consistently maintained higher moisture content in the surface horizon, which is critical for early crop establishment and root proliferation. This improvement in moisture retention under zero tillage can be attributed to the absence of mechanical soil disturbance and the preservation of crop residues on the soil surface, which collectively reduce evaporation losses and improve infiltration dynamics.

Supporting these findings, McVay et al. (2006) also observed elevated moisture levels in the topsoil under no-till conditions compared to ploughed soils, reinforcing the notion that reduced tillage intensity contributes positively to soil water conservation. The structural integrity of the soil under zero tillage, coupled with the protective mulch layer, plays a pivotal role in moderating soil temperature and minimizing moisture fluctuations. Furthermore, Bhatt and Khera (2006) reported that minimum tillage combined with surface mulching led to appreciably higher moisture content, underscoring the synergistic effect of reduced soil disturbance and residue management in enhancing soil water availability.

These observations collectively highlight the potential of zero tillage as a moisture-conserving practice, particularly in regions where water availability is a limiting factor. By improving the soil's capacity to retain water in its profile, especially in the critical upper layers, zero tillage not only supports sustainable crop production but also contributes to long-term soil health and resilience under changing climatic conditions.

CONCLUSION

Zero tillage significantly influences soil physical properties, offering both challenges and long-term benefits. Initial increases in bulk density and surface penetration resistance are common, yet these effects diminish over time due to improved biological activity and soil aggregation. Enhanced hydraulic conductivity and infiltration rates under zero tillage result from preserved macropores and residue cover, which protect against surface sealing. Improved moisture retention, driven by reduced evaporation and increased organic matter, supports better water availability for crops. Collectively, these changes contribute to improved soil structure, resilience, and water dynamics, reinforcing zero tillage as a viable strategy for sustainable agriculture across diverse agro-climatic regions.

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