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Soil Compaction Induced by Different Tillage Systems and its Impact on Growth and Yield of Maize (Zea Mays L.) : A Review

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Abstract

Maize (Zea mays L.) cultivation faces challenges with compaction due to mechanical tillage, which affects the physical properties of the soil necessary for growth. This pressure from interactions between machinery and soil during plowing modifies bulk density, resistance to root penetration, and the amount of penetrating water. Extended tires play a vital role in this process. This chapter examines this complex relationship and focuses on its deleterious effects on corn root growth, nutrient availability, and overall grain performance. Although studies show significant yield reductions under severe stress, the globally agreed critical level remains elusive, and further research into soil dynamic factors affecting maize productivity is warranted. This vision describes strategies for improving agricultural practices in the face of the challenges of mechanized tillage. Soil compaction, one of the major concerns in corn cultivation, profoundly affects plant growth. Mechanical stresses resulting from tillage modify soil properties and affect bulk density, root penetration, and water movement. Compacted soil limits access to air and water and prevents root respiration and nutrient uptake. This multifaceted limitation results in poor seed germination, reduced yield, and increased susceptibility to root diseases. Mitigation strategies include reduced tillage, precision agriculture, conservation tillage, and deep tillage. Although some pressure can be beneficial for fluid retention, excessive levels pose risks. The comprehensive approach includes soil assessment, controlled rotation tillage, cover crops, mechanical aeration, optimal equipment design, and continuous monitoring. Education and adaptive practices are essential for sustainable management of soil compaction.

Keywords:* *Root penetration resistance, Soil characteristics, Critical level, Mitigation strategies

I. INTRODUCTION

Maize (Zea Mays L.) is considered one of the economically important industrial and fodder crops. Yellow maize production is greatly affected by soil preparation methods and cultivation methods (Imran et al., 2021). Mechanical compaction caused by repeated plowing operations is the most influential factor in the growth and production of yellow maize. Soil compaction results from compaction of tractor tires and agricultural machinery during plowing operations. To improve maize cultivation, the effect of soil compaction caused by mechanized tillage on the movement of water and nutrients and crop growth must be understood (Johnson and Brown, 2019). Mechanical soil compaction caused by the movement of tractors and agricultural equipment is a process that has negative effects on the soil as a result of the convergence and compaction of soil particles, which leads to a reduction in the apparent soil density, total porosity, and soil permeability. The negative impact of soil compaction is not limited only to the physical properties of the soil, but it also has a significant negative impact on

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soil health and sustainability. Tillage operations are one of the most effective operations in soil compaction (Salokhe and Ninh, 1993). In this review, we highlight the very complex relationship between mechanical tillage operations and soil compaction, as well as address the challenges related to the phenomenon of soil compaction, and provide solutions and strategies that can reduce its harmful impact.

Soil compaction resulting from mechanical tillage operations occurs when soil compaction caused by tillage machinery exceeds the threshold of soil plasticity and resistance (Misiewicz et al., 2015). The compression of the surface soil layers is due to the impact of tractor tires on the soil surface, as stresses are transferred from the tires to the surface soil layer. Compaction of the subsurface soil layer occurs due to increased axial loads acting on the soil (Siczek et al., 2015; Shah, et al., 2017). In order to address this, it was classified (Aitana et al., 2013). Mechanical soil compaction caused by mechanized tillage is divided into two categories: superficial compaction (0-30 cm) and compaction resulting from mechanized tillage at soil depth (> 30 cm). The effect of different tillage equipment on soil compaction is the damage to soil structure at the surface soil layer (0-30 cm), and this is attributed to increased compaction of tires in contact with the soil. On the other hand, subsurface soil layers (> 30 cm) are exposed to pressures resulting from high axial loadsBotta et al., 2007; Arvidsson and Keller 2013). Despite the many factors affecting soil compaction, such as the influence of weather and environmental factors, the processes of preparing the soil for agriculture, represented by plowing operations, are the main cause of soil compaction Misiewicz et al., 2015; Abd-Wahed et al., 2022). Choosing appropriate tillage equipment for soil type and conditions is important to improve growth of maize (Mwiti et al., 2022). However, traditional tillage operations can lead to increased soil compaction within arable soil layers. As a result of the above, the European Union considered that mechanical soil compaction resulting from mechanical tillage operations is a characteristic that indicates soil degradation worldwide (Jones et al., 2003).

Many previous studies focused on the effect of mechanical tillage on the growth and productivity of maize, which revealed noteworthy contradictions. Specialized studies and field experiments carried out by many researchers in soil and plant sciences and agricultural engineers in particular have confirmed that there is a significant connection between soil compaction and mechanical tillage operations. The present review paper focused on the effect of mechanical tillage operations resulting from soil compaction on the agricultural soil layer in which maize roots grow and spread, as well as highlighting both the growth and productivity of maize induced soil conditions subject to compaction.

The effects of soil compaction resulting from mechanical tillage operations on soil properties when preparing the soil for planting corn:

Soil compaction resulting from mechanical tillage operations has significant effects on the physical, chemical and biological properties of the soil. Some studies have revealed that critical levels beyond which the root system of the corn crop is weakened, leading to a decrease in plant productivity (Radford et al., 2007; Ji et al., 2007). The critical limit for soil compaction index ranges between 1.5-3 MPa. The critical limit for bulk soil density lies within the range of 1.2-1.52 mg m3. (Colombi and Keller, 2019). The compaction of soil layers is caused by many factors, the most important of which is the size of agricultural equipment, as well as the frequent passage of heavy equipment, which negatively affects the natural properties of the soil. This can lead to a decline in soil productivity as a result of decreased soil permeability and water seepage, as well as increased soil erosion, which affects on crop growth and productivity (Dejong-hughes et al., 2001; Huber et al., 2008). Many studies have confirmed that compaction of soil layers resulting from increased traffic of agricultural equipment in agricultural fields has a negative impact on soil health and productivity (Raper and Kirby, 2006;

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Radford et al., 2007; Ji et al., 2013). One of the important ways to measure soil compaction resulting from mechanical tillage operations is the resistance of the soil to penetration (Sweeney et al., 2006). ; Shaheb, 2020).

Mechanical soil compaction resulting from mechanical tillage operations has a significant impact on coarse to medium-fine soil, which may be attributed to many factors such as the size of the tires and their contact area with the soil, the weight of the agricultural tractor, the number of times agricultural equipment passes, and the tillage techniques and equipment used to prepare the seed bed. , significantly on coarse to medium fine soils (Gozubuyuk et al., 2014). Many researches have revealed that soil compaction resulting from frequent passage of heavy agricultural equipment can negatively affect the penetration and spread of roots in the soil, the size of soil pores filled with water, hydraulic conductivity, and the good aeration capacity of the soil (Obour and Ugarte, 2021; Wang et al., 2022).). In addition, compaction resulting from mechanized tillage operations affects soil size distribution, soil structure, and the availability of nutrients that maize roots can absorb (Chyba et al., 2014; Rut et al., 2022).

Many investigations have shown a considerable reduction in soil infiltration rates at high soil compaction induced by tractor tires, particularly in light soil (Obour and Ugarte, 2021). The plowing operation raises stresses, and soil bulk density, on the contrary, reduces the porosity of the soil, permeation, and soil hydraulic characteristics in corn-cropped soils (Kutílek, 2004). Also (Keller et al., (2013). observed that the alteration in the volume, constitution, spatial structure of soil aggregates, and void ratios, because of compaction caused by the plowing machine

An increase in axial loads (from 1 to 3 kN) and the number of lanes of agricultural equipment and tractors significantly help in increasing soil compaction resulting from seed bed preparation operations (Salokhe and Ninh, 1993). The maximum extent of soil compaction occurs after the first pass of the tractor wheels, as successive passes lead to increased soil compaction. The passage of tractor wheels for the first time in the field increases the bulk density and resistance of the soil to penetration by an average of 7% and 6%, respectively (Badalıkova, 2010).

Tractor passes in agriculture fields can have more negative impacts on soil health and its various properties compared to intensive planting strategy, resulting in considerable shifts in soil properties. a study carried out by Blanco-Chan et al. (2006) reported that increased wheel traffic to two passes led to a 19% boost in BD (from 1.20 to 1.39 Mg m−3), when increasing the percentage of 74% in (PR) from 1.78 to 3.10 MPa, and increasing in an in shear strength from 0.23 to 0.61 MPa, (165% increase) compared to agricultural fields without traffic at depths of 0–75 cm.

In traditional tillage techniques, 85% of the total area planted in corn was conducted in several tractor passes on the soil surface (Kroulík et al., 2011; Nassir et al., 2023a). The increasing passes in agricultural fields from 2 and 3 times for traditional tillage approaches led to increasing soil compaction by 35% and 1602%, respectively. These replicated pass events yielded considerable harm to soil aggregate as well as deterioration of soil health and properties, as noted in many studies (Hula et al., 2009; Pulido-Moncada et al., 2019).

An investigation carried out by Shaheb et al. (2018) in a specific maize and soybean rotation in an Illinois province exhibited that agriculture practices conducted by heavy tractors resulted in lower soil pores volume, due to soil compaction caused by increased inflation pressure of tractor tire system reach to 0.19 MPa compared to decreased inflation pressure of tractor tire system reach to 0.05 MPa in loam soil. At inferior inflation pressure tires of tractor.

Raised agricultural processes using heavy agricultural equipment were offered to deteriorate soil structure, particularly at using in saturated wet soil conditions (Botta et al., 2010). Arvidsson and Keller (2007) reported that the low tire inflation pressure at a shallow depth of 10 cm led to a reduction in the soil stresses, in the contrary increasing the axle load resulted in increasing the stresses in deep soil

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layers. Tires with lower inflation pressures (0.19 to 0.22 MPa) were effective in reducing soil PR (0 to 700 mm depths) compared to tires with higher inflation pressure (0.25 MPa) (Antille et al., 2013). The low inflation pressures of tires (0.15 to 0.20 MPa) were sufficient in decreasing the penetration resistance of soil (0 to 80 cm depths) compared to tires of the tractor which have a higher inflation pressure reach of 0.25 MPa (Antille et al., 2013). In a study, of continuous long years on acceptable clay soil, topsoil structural deterioration was caused by increased pressure tires, on the contrary, major axle loads were overlooked to result from the most influential compaction in deep soil layers (Botta et al., 2010). The pressure of the ground range of 150–240 kPa was revealed to decrease soil water infiltration rate in the agricultural fields which faced compacted by more than 80% in comparison with uncompact soil (Chyba et al., 2014). The compaction of soil can considerably decrease water infiltration soil body, resulting in boosted runoff spread pollution (Godwin et al., 2015). In an investigation to determine the influence of mouldboard plow kinds on the PR of soil Nassir (2018) reported that the highest PR of soil was registered by the helical plow kind, followed by the deep digger plow type which registered a PR value of 0.816 Mpa and the lower was the general-purpose plow kind which registered a PR value of 765 Mpa. Raised PR of soil reaching 2 MPa has been indicated to have a considerable influence on corn root spread in deep soil layers, and productivity (Aase et al., 2001).

The critical range for corn crop rooting and growing reaches 3.0 MPa depended on (Lipiec and Hatano, 2003), in contrary (Kulkarni et al., 2010) propose that the descending threshold for compaction induced by tillage machines and equipment, reach 1.4 MPa to obtain the best crop growth. Investigators handling dynamic soil determining factors suggest a critical PR level of 1.52 to 3.02 MPa as a limit for soil compaction resulting from mechanical tillage that can influence corn growth (Håkansson and Reeder, 1994).

A study carried out by Blanco-Canqui et al (2010) revealed a considerable boost in BD, PR, shear, and tensile strength of soil in mechanical tillage conditions, additionally highlighting the compaction influences on soil health. Besides, Hoeft et al. (1947) noted that the lower soil pores increased tire inflation pressures to 0.17 MPa in comparison with tractors that have low-pressure tire systems reah 0.04 MPa in corn-cropped in silt clay loams. Further, Shaheb et al. (2020) observed a 17.9% boost in macrospores at low tire inflation pressures in comparison with typical tire inflation pressures in the plowing operations of sandy clay loam soil. These conclusions emphasize the vital role of PR and compaction indices in impacting soil properties and, thus, the growth and grain yield of corn.

The impact of the number of passes on soil penetration resistance:

The pressure exerted by the tires on the soil surface (the weight of the tires per unit area of contact) results in its compaction. This compaction is defined as the downward and lateral movement of soil particles due to the applied pressure. The soil cannot resist this compression, leading to the convergence and interlocking of soil particles, causing a reduction in soil volume and an increase in its apparent density. From another perspective, this increase in the weight of solid soil particles per unit volume is referred to as stress (Mirzavand and Moradi-Talebbeigi, 2021).

The passage of machinery over the soil surface is considered one of the most significant factors leading to its compaction, thereby increasing its apparent density and reducing its moisture content (Nassir et al., 2023). Ahmad et al. (2018) found that increasing the number of passes of the double-disc harrow in clayey soil from one to three times resulted in an increase in soil penetration resistance from 1.53 to 1.747 Mpa, representing a 13.98% increase. Agherkakli et al. (2011) indicated that an increase in equipment passage over the soil surface led to an increase in soil penetration resistance from 0.750 to 1.20, 1.35, and 1.45 Mpa for no passage, one pass, and five passes, and nine passes, respectively. They also reported that soil compaction increases with a decreasing trend, meaning that an increase in the number of passes leads to a decreasing rate of soil compaction by 60%, 12.5%, and 7.40% for the transitions from 0 to 1, 1 to 5, and 5 to 9 passes, respectively. The lowest pressure occurs with a higher

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number of passes because soil particles are closer to each other, resulting in increased frictional forces between soil particles.

Meselhy and Khater (2020) concluded that the use of a 225 kg plow in sandy loam soil resulted in a 37% and 96% increase in soil penetration resistance in traffic and non-traffic areas, respectively, for traditional farming, and approximately 15% and 31%, respectively, for conservation farming. Additionally, Ten Damme et al. (2021) observed a significant effect of increasing the number of tractor tire passes on soil surface. Increasing the number of passes from one to six led to a 25.83% increase in penetration resistance. They attributed this to an increase in convergence of soil particles, reducing soil porosity and increasing its apparent density, thereby increasing soil penetration resistance.

Impact of Tillage-Induced Compaction on Maize Grain Yield

Researchers have undertaken both short-term and long-term investigations with the goal of understanding the effects of tillage-induced compaction on maize biomass and grain yield (Raghavan et al., 1979; Obour and Ugarte, 2021). These studies consistently reveal substantial reductions in maize yields when subjected to severe tillage-induced compaction (Raghavan et al., 1979; Colombi and Keller, (2019). The vitality of maize crops, crucial for determining maize grain mass yield (GMY), experiences a decline in the face of increased tillage-induced compaction Obour and Ugarte, 2021; Hargreaves et al., 2019; Ram et al., 2020). For example, Shaheb (2020) reported a reduction of maize yields by 4.13% and 2.62% in the 2nd and 3rd years, respectively, due to compaction induced by tractor tires during mechanized tillage. Severe compaction from tillage machinery resulted in a staggering 50% decline in maize GMY Voorhees et al., 1989; Shaheb et al., (2021). Nevertheless, Olubanjo and Yessoufou, (2019). reported an 18% yield decline, while Godwin et al. (2019) reported a 10-15% decline in GMY due to tillage machine-induced compaction. On average, tillage machine-induced compaction led to a 34% decrease in maize GMY in medium-textured soils and a 15% decrease in fine-textured soils (Obour and Ugarte, 2021). Although no significant effect on grain yield was observed in mechanized tillage-induced compacted clays (Keller et al., 2013), there was a 50% reduction in grain yield in heavily mechanized compacted sandy loam soil (Antille et al., 2019), as well as in both clay and loam soil (Adejumo et al., 2016)]. According to (Voorhees et al., 1989), there was an 18% decrease in maize yield for every 0.1 Mg m^{-3} increase in bulk density above 1.3 Mg m-3 in tillage-induced compacted soils with 30–40% clay content.

Mechanized tillage yield simulation models predicted a notable 23 to 30% reduction in maize grain yield under all axle loads of tillage machinery (Klopfenstein, 2016). In contrast, (Arvidsson and Håkansson, 1991). reported higher maize grain yields due to improved soil-root contact in moderately tilled compacted soils compared to compacted soils. Surprisingly, mechanized tillage-induced compaction did not significantly deter maize yields over time, as soil texture, organic matter, limiting water range, and clay mineralogy countered the severities of crop rooting and nutrient uptake (Reichert et al., 2009; Muhsin et al., 2021). The inconsistencies in the effects of tillage-induced compaction on overall maize growth and yield could be attributed in part to the influence of other dynamic soil factors and environmental covariates (Keller et al., 2019).

The susceptibility of maize yields to critical effects, levels, and limits of mechanized tillage-induced compaction remains a topic of debate. Researchers have yet to establish a universally agreed-upon critical level of mechanized tillage-induced compaction that would significantly reduce maize yields, independent of other soil, environmental conditions, or nutrient status. Further research is imperative to unravel the influence of additional dynamic factors such as soil structure, moisture levels, and organic matter content in counteracting the effects of mechanized tillage-induced compaction levels on maize yield (Olubanjo and Yessoufou, 2019).

Effects of Mechanized Tillage-Induced Compaction on Root Development

Plant root growth and development play an important role in impacting the growth and productivity of corn crops. It has been exhibited that automated stress produced by plowing practices has sometimes positive but negative influences higher on the spread and growth of roots (Wang et al., 2022).

Mechanical plowing stress had negatively affected maize root length, fresh and dry root mass, shoot elongation, height, and leaf area index. However, negative influences are due to mechanical plowing biological plant parameters such as plant length, root length, area index, and mass of roots. the previous parameters decreased from 27.22 to 69% under compacting soil in comparison with soil without compacting resulting from mechanical plowing (Millington, 2019). Although these negative influences in compaction soil give some advantages to this soil such as improving soil water storage and increasing the fixed roots of corn plants (Burak et al., 2021).

However, machinery-induced compaction restricted access of maize roots to available water pools, affecting soil pore numbers, gross porosity, and infiltration rate (Duruoha, 2007). As reported by Dejong-hughes et al., 2001, the presence of a dense mechanically induced hard layer over a water-impermeable soil impeded aeration of maize roots, creating an anaerobic environment that limited nutrient uptake. There are conflicting results regarding the causes and effects of uptake. Water and nutrients in maize, whether directly attributable to machine-induced tillage compaction or not. For example, (Liebeck and Hatano, 2003) observed an increase in root water uptake in soils with moderate machine-induced compaction (bulk density of 1.5 mg /m3). Compaction from mechanized tillage at the topsoil level improved soil root density for the shallow-rooted architecture, resulting in an increased rate and intensity of corn water uptake (Nosalewicz and Lipiec, 2014). However, these effects led to Increased drying of the topsoil and restricted growth of maize roots in deeper layers, resulting in reduced access to water and nutrient uptake from subsoil layers (Siczek et al., 2015).Despite the restrictive effects on penetration resistance of maize roots, a direct result of mechanical tillage They are: Induced stress reduces the efficiency of water and nutrient use (Raghavan et al., 1979). Regarding nutrient availability and uptake in maize, mechanical stress induced by tillering affected various aspects, including nutrient availability, concentration, transformation, diffusion, uptake, uptake, and transport (] Bhadoria et al., 1991; Ren et al., 2022).). . According to (Guan et al., 2014), the limitations on nutrient transport due to stress were dependent on the available water and applied nutrient levels. Plowing-induced compaction did not affect ion concentration, diffusion and mass transfer in well-watered, fertile soils, thanks to increased hydraulic conductivity and water retention (Becker et al., 2022). However, beyond certain limits, increasing compaction and bulk density of soil reduced ion diffusion coefficients due to increased pore tortuosity and resistance to root penetration (Liebeck and Hatano, 2003). Significantly, a decrease in maize root uptake levels of nitrogen (N), potassium (K), magnesium (Mg), and sodium (Na) was observed by 13.5%, 51.4%, 50.4%, and 51.5%, respectively. At the soil. The cone index (CI) increased from 1.5 to 5.2 MPa (Parlak, and Parlak, 2011). On the contrary, machine-induced compaction enhanced N utilization due to increased soil-root contact, especially with a higher proportion of fine roots during maize seedling stages (Wu et al., 2022). The effects of soil erosion caused by field systems on plant growth and yield can be established in the diploma of soil compaction (Shaheb et al., 2021; Nyakudya and Strosnijder, 2014). Soil erosion due to mechanical sliding can cause:

1- Low cost of seed germination.

2- Poor plant growth, reducing organic production and grain yield.

Plant roots are also susceptible to diseases in compacted soils due to triple drainage and lack of aeration.

Considering that soil leaching inhibits plant growth and reduces plant yield and soil viscosity inhibits root growth, allowing water and vitamins to enter the plant (Figure 1), effects of a the ground shrinkage

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experienced is greater in severe weather conditions. in which subterranean properties are critical for plant life. Furthermore, compact soils lose their ability to effectively buffer problems and support crop growth.

The following are the most important effects of soil stress due to agricultural activities.

1. Deterioration of the soil structure

2. The overall porosity and permeability of the soil decreases internally

3. High groundwater table and poor soil water holding capacity

Anan. The sensitivity of the soil to salinity increased, mainly due to increased electrical conductivity in the saturated soil.

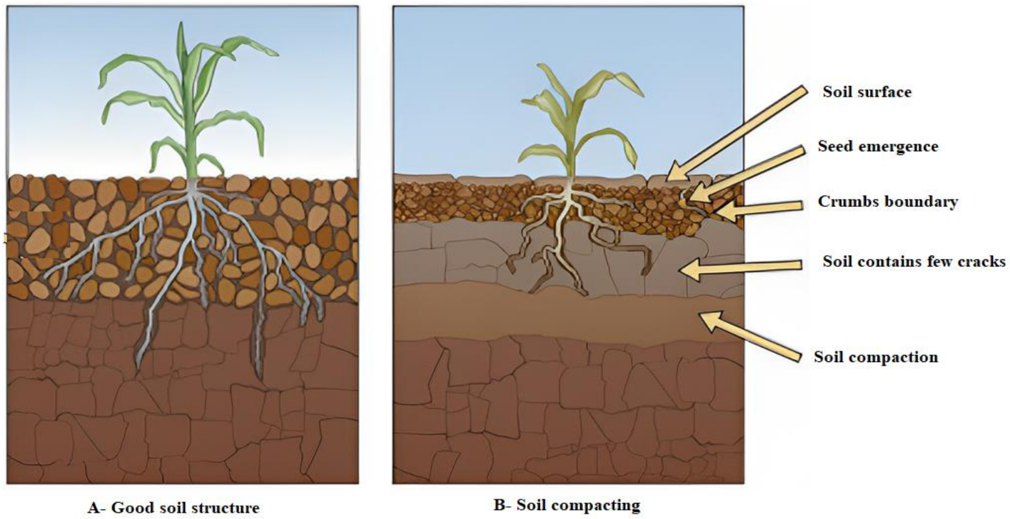

Figure 1. Effect of soil compaction on maize growth

Soil compaction measurements and results:

In soil hardness measurements, there may be a consistent inverse courting between resistance to soil infiltration and soil moisture. This dating has other dimensions: soil erosion modifications pore exceptional, to some extent increasing capillary water potential, and as a consequence modifications in soil moisture content Dedousis and Bartzanas (2010) use a threshold values were installed for the degradation of soil compaction properties, as precise in Table 1 .

The practical advantage of metering is further showed via the nearly linear dependence between soil resistance, measured by the penetration approach, and bulk density studied with the aid of Ratonyi (1998). Lengthy-term effects on the consequences of extended periods of low tillage or shallow discing on soil shrinkage and moisture content. Notably, the relationship between infiltration resistance, bulk density, and soil moisture exhibited linearity. Changes caused by soil compaction have a negative effect on soil bodily houses, maximum incredibly in extent discount, which in turn affects a huge range of physical homes along with porosity, wind and water content material energy, thermal conductivity of the soil, and so forth

Water, a key factor in biomass production and soil fertility management, experiences changes in content material, availability and movement due to soil compaction Excessive soil moisture and poor conditions seems to be degradable, indicating that soil erosion drastically complements the physico–

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chemical biological strategies ylich et al. , 2010). The bodily houses of the soil impact the microclimates of the plant, in particular water, temperature and wind regimes.

Table 1. Limit values of soil properties

Soil property	Soil type					
	j[c]	jv[c], jh[c]	h[c]	Ph[c]	hp[c]	p[c]
Porosity (vol.%)	<48	<47	<45	<42	<40	<38
Reduced bulk density (g cm^{-3})	>1.35	>1.40	>1.45	>1.55	>1.60	>1.70
Penetrometric soil strength (MPa) –	2.8–3.2	3.2–3.7	3.7–4.2	4.5–5.0	5.5	6.0
at soil moisture content (wt.%)[a]	28–24	24–20	18–16	13–15	12	10
Minimum air capacity (vol.%) [b]	<10	<10	<10	<10	<10	<10

[a]If soil moisture lies outside the interval given in the following line, then for each weight percent of soil moisture either add 0.25 MPa to the value of critical resistance (*lower water content*) or subtract 0.25 MPa from the value of critical resistance (*higher water content*)

[b]10% is the average value of minimum air porosity; in vertical pore orientation the limit value reduces to 8 vol.%, in horizontal pore orientation it increases up to 15 vol.%. The limit value varies with crops (root crops 12%, cereals 10%, and forage crops 8% (Dedousis and Bartzanas, 2010)

[c]j = c [clay]; jv, jh = ce, cl [cleyey, cleyloamy]; h = l [loamy]; ph = sl [sandy-loamy soil]; hp = ls [loamy-sandy soil]; p = s [sandy soil]

Mitigation techniques for agricultural-prompted compaction

Several strategies may be used to mitigate the bad results of mechanized tillage on corn growth and yield. One manner is to incorporate soil smoothing strategies which include subsoil compaction. However, research indicates that subsoiling does no longer offer a great deal benefit in enhancing wheat crop performance as compared to conventional tillage strategies (Obour and Ugarte, 2021; Wang et al., 2022).).

Another alternative is the use of precision tillage techniques to optimize planting schedules and reduce soil compaction. By the use of improved machinery with lower soil tensions and reducing tractor passes, farmers can reduce the hazard of soil compaction even as preserving excessive yields (Shaheb et al., 2006). (2021).

In reaction to the demanding situations posed with the aid of mechanization in agriculture, researchers have proposed strategies aimed toward lowering its bad results The hints replicate the complexity of the difficulty:

Low tillage machine axle load and occasional tire air stress:

Some researchers suggest low agricultural machinery axle weight and coffee tire air stress as a manage degree (Godwin et al., 2017; Nassir et al., 2023b).

Grinding machines:

Others recommend mechanical interventions consisting of ordinary subsoil compaction, strip tillage, and managed visitors to manipulate and manage compaction because of mechanized tillage Shaheb, (2020).

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Biodiversity conservation and restoration:

Conservation agriculture, which includes strip farming and organic count retention, were proposed as powerful strategies to mitigate the consequences of tillage mechanization (Brevik et al., 2002).)..

The better bulk density related to soil compaction exacerbates these troubles, making it more difficult for roots to access nutrients and water. Microbial activity is also affected, impacting nutrient cycling and availability. Additionally, the conducive environment created by compacted soils can increase the incidence of root illnesses (Colombi and Keller, 2019). Poor seed germination and crop status quo further make a contribution to decreased yield ability. In essence, soil compaction acts as a multifaceted constraint on plant boom, necessitating powerful soil management practices to mitigate these adverse effects and promote healthier plant improvement. Techniques including deep tillage, cowl cropping, and minimizing discipline site visitors may be instrumental in addressing soil compaction troubles (Sidhu, and Duiker, 2006).

Soil compaction can have each suitable and undesirable outcomes on plant growth. Voorhees et al. (1978) shows that crops respond to soil compaction as shown in Figure 2.

Dry climate: In a dry 12 months, at very low bulk densities, yields regularly increase with a slight increase in soil compaction.

A slightly compacted soil can accelerate the rate of seed germination because it promotes top seed-to-soil touch. This is why corn planters have been specially designed to offer moderate compaction with planter-established packer wheels that observe seed placement.

As soil compaction will increase past most reliable, yields begin to decline. In dry years, soil compaction can result in stunted, drought-harassed flora due to reduced root increase. Without well timed rains and nicely-placed fertilizers, yields will reduce.

Wet climate: In moist climate, yields lower with any increase in compaction. Soil compaction in wet years decreases soil aeration, increasing denitrification. The

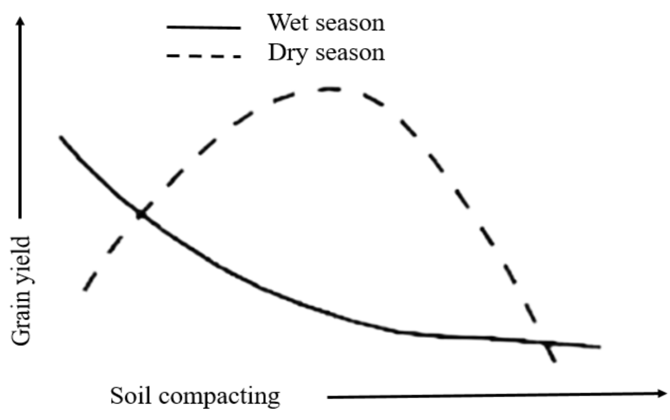

Figure 2. Relationship between soil compaction and grain yield

Methods for reducing soil compaction: a comprehensive and dynamic approach to sustainable agriculture

There are different strategies to reduce soil compaction, and these strategies include preventive measures and remedial methods. It is carried out by conducting a comprehensive soil assessment using special equipment such as soil resistance to penetration meters to determine the layers of compacted soil and the depth of the soil layer subjected to compaction due to the passage of machines and tractors. Controlled Traffic Farming (CTF) methods can be used as one of the strategies used to reduce soil compaction, as it limits the number of passes in the agricultural field, which leads to reducing the passage of heavy equipment on the surface of the agricultural field (Godwin et al., 2015). No-tillage or reduced-tillage systems are also important in maintaining different soil structures and characteristics. Using agricultural rotations as a precautionary measure is a successful strategy in dealing with soil compaction, which protects the soil and improves its structure and properties (Shehab et al., 2021). Tillage equipment such as a subsurface plow can be used as a strategic solution to reduce soil compaction by breaking up the compacted soil layers. The amount of air in the tires is within the appropriate limits for the type of soil and its conditions to ensure the appropriate pressure inside the tires. Use wide tires with low pressure to ensure that the air pressure is spread evenly. Adding soil amendments, such as organic fertilizers, is an important strategy to reduce soil compaction, which improves soil aeration, water seepage, and microbial activity (Antille et al., 2016; Augustin et al., 2020). Constant follow-up and improvement of agricultural practices on scientific foundations based on field experiments and good soil management ensures a rapid response to reducing soil compaction. Various educational and training programs for farmers, agricultural engineers, and workers in the agricultural sector also help in collective understanding that improves soil health and enhances its sustainability, ensuring increased soil productivity and improved soil properties (He et al., 2020).

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