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Mechanized Tillage-Induced Compaction and its Effect on Maize (*Zea Mays* L.) Growth and Yield - A Comprehensive Review and Analysis

Frankline Mwiti [1, 2*], Ayub Gitau [2], Duncan Mbuge [2], Paula Misiewicz [3], Ruth Njoroge [4], Richard Godwin [3]

[1] Department of Agricultural and Biosystems Engineering, University of Eldoret, P. O. Box 1125-30100, Eldoret, Kenya.

[2] Department of Environmental and Biosystems Engineering, University of Nairobi, P. O. Box 30197-00100, Nairobi, Kenya.

[3] Department of Agricultural Engineering, Harper Adams University, Newport, Shropshire, TF10 8NB, United Kingdom.

[4] Department of Soil Science, University of Eldoret, P. O. Box 1125-30100, Eldoret, Kenya.

[*] *frankline.mwiti@uoeld.ac.ke / franklinemwiti2@gmail.com*

Abstract

While agricultural engineers are concerned with physico-mechanical properties of arable soils, agronomists tackle crop management husbandry as soil scientists' dwell on bio-chemical properties. Such diverse and isolated interests seldom report any interaction or integrated effect of biological, agronomical, and physico-mechanical parameters of soils affected by mechanized tillage induced compaction. This paper reviews intrinsic effects of mechanized tillage-induced compaction on soil-water-nutrient dynamics, crop growth, and yield of maize. Mechanized tillage induced top and subsoil compaction are caused by soil-tyre contact stresses and machinery axle loads respectively. Mechanized tillage-induced compaction reduced maize nutrient absorption levels of Nitrogen (N), Potassium (K), Magnesium (Mg), and Sodium (Na) by 13.5%, 51.4%, 50.4% and 51.5% respectively. Maize N uptake was least affected by tillage-induced compaction compared to P and K. Mechanized tillage-induced compaction improved maize root intensity, root mass and volume by over 50% in compacted topsoils but decreased by 90% in the sublayers. Maize root length, fresh and dry root mass, shoot elongation, height, and leaf area index reduced by 29%,

39.1, 37.8, 27.1, 10-21, and 67.8% respectively. In contrast, mechanized tillage-induced compaction improved soil-seed-soil-root contacts, soil- root-bonding root density and diameter, stiffness, anchorage, and root- lodging resistance of maize. Mechanized tillage induced compaction index and bulk density range of 1.5-3.0MPa and 1.2-1.52 Mg/m3 respectively are the critical levels beyond which maize rooting, growth and yield are impaired. Dependent on dynamic soil covariates, viz limiting water range, matrix suction potential and organic matter content; mechanized tillage-induced compaction reduces maize yield by as high as 50%.

Keywords: Tillage Machine Axle Load, Tyre Inflation Pressure, Penetration Resistance, Cone Index, Nutrient Uptake, Soil Compaction.

1. Introduction

Due to increased demand for food and the rising cost of maize production, researchers are pursuing sustainable mechanized tillage practices that provide a favorable soil-root environment for improved maize growth and yields. However, mechanized tillage causes soil compaction that eventually disrupts the bio-physical-mechanical state of maize-cropped soil-root ecosystem [1], [2]. Mechanized tillage-induced compaction ensues when soil loading stresses from tillage machinery exceed the elastic threshold limit and soil bearing strength [3]. While soil-tire contact and wheeling stress load at the soil-wheel interface are blamed for topsoil compaction, subsoil compaction is caused by high axle loads [4], [5]. Accordingly, [6] suggested that mechanized tillage-induced compaction be divided into two categories i.e., Surface horizon (0-30cm) machine-induced compaction and subsoil tillage-induced compaction (> 30cm). Multilayered soil loading stresses by tillage machine-induced compaction showed topsoil (0-30cm) structural damage from high tire-ground contact pressures while high axle loads induced the most significant compaction damage in subsoil (> 30cm) depth [7], [8]. Nonetheless, high axle loads and wheeling stresses from tractive and trailed pneumatic tires were the primary cause of tillage-induced compaction [9]. Plate 1 shows a visual characterization of mechanized tillage-induced compaction of maize-cropped soil at 4cm root depth against a possible 60 - 80cm [10].

Plate 1. Mechanized tillage-induced compaction of the soil-root environment in Northrift, Kenya, (a) Maize rooting depth restricted to 4 cm (b) Impaired maize rooting penetration.

Soil-tillage machine interactions play a critical role in the edaphic functioning of soil medium for optimal maize growth [11]. However, soil machine interactions in tillage increases the compaction of arable soil layers due to the rising trend of mechanized tillage. The European Union recognizes mechanized tillage-induced compaction as a severe form of soil degradation globally [12]. According to [13], approximately 70.5 million hectares of the world's arable land has been compacted by mechanized tillage as shown in Figure 1.

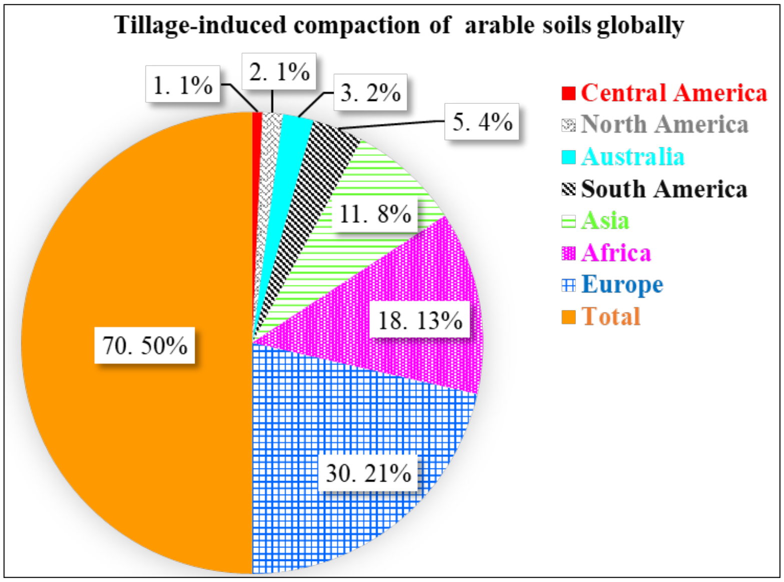

Fig. 1. Extent of mechanized tillage-induced compaction across various continents. Modified from [13].

The effects of mechanized tillage-induced compaction on the growth and yield of maize have been reported and quantified with significant variations and inconsistencies over the years. Specialized studies by soil scientists, agronomists, and agricultural engineers isolate the interaction effect of mechanized tillage-induced compaction with agronomic and soil science practices such as water and fertilizer use efficiency. This paper reviews the influence of mechanized tillage-induced compaction on maize-cropped soil root environment and its effect on maize growth and yield. Published works addressing maize crop establishment, overall growth, and yield in mechanized tillage systems were reviewed systematically as shown in Figure 2.

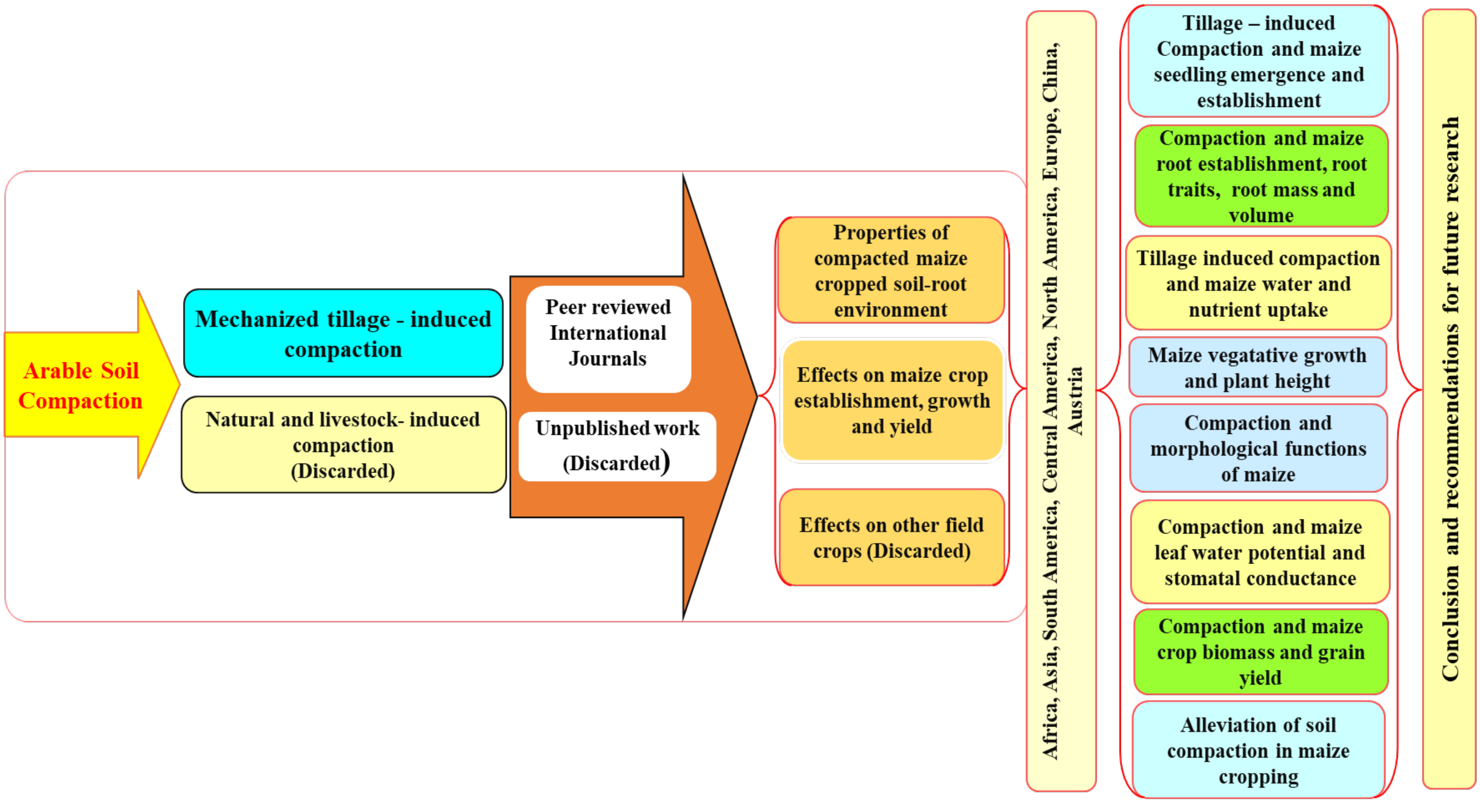

Fig. 2. Systematic review and analysis of the effects of mechanized tillage-induced compaction on maize production

2. Properties of Mechanized tillage-induced Compaction of Maize Cropped Soils

Maize grows well in Ferralsols, Acrisols, Alisols, Nitisols, Luvisols Vertisols, Gleysols and Planosols [14]. The soils must be deep, well-drained, and aerated, with adequate organic matter and nutrient supply for optimal growth [15]. According to [16], the most optimal soils are clay loams, sandy clays, sandy loams, sandy-clay loams, and silty clays with less coarse, medium, to medium-fine textures. However, these properties render the soils susceptible to mechanized tillage-induced compaction emanating from wheeling loads, axle loads, number of tractor passes, and tillage methods and implements [17].

According to [18], the edaphic environment of coarse to medium-fine-textured soils was significantly affected by mechanized tillage-induced compaction. As such tractor axle loads, wheel passes and tire inflation pressures increased soil bulk density (BD), root penetration resistance, reduced volume of water-filled pores, soil-air permeability, and hydraulic conductivity of maize-cropped soils [19]. Further, mechanized tillage-induced compaction affects the soil texture, aggregate structure, matrix potential, porosity, infiltration capacity, and mineral nutrient availability [20]. For instance, [21] reported an over 80% reduction in soil infiltration rates under high soil-tire ground pressures (200-250 kPa) from tractor wheeling of sandy loams. According to [22], mechanized tillage increased soil strength and BD while reducing pore volumes, infiltration rates, and soil hydraulic, characteristics of maize-cropped soils. Additionally, tillage machine-induced compaction altered the size, shape, and spatial arrangement of soil clods, void ratios, and aggregate structure [23], [24]. Furthermore, [25] and [26] showed a decline in soil air permeabilities in wheeled tillage tracks of maize rows due to increased penetration impedance and BD. Machinery-induced compaction stresses destroyed macropores which are important for aeration and free drainage of soil [27]. As such tillage-induced stress loads increased soil strength and decreased the soil micropores [28]. The micropores of maize-cropped agricultural soils were thus, deprived of adequate drainage, water retention, and aeration [29]. Moreover, tillage machinery axle loads reduced gas diffusivity, and pore volume and increased BD of subsoil layers (50cm depth) in sandy loams [30]. Thus, mechanized tillage-induced compaction restrained the aeration status and hydraulic characteristics of maize-cropped soils [31], [32]. [33] reported an increase of 19% (from 1.16 to 1.38Mg m-3), 74% (from 1.78 to 3.10MPa), 165% (from 23 to 61kPa), and 153% (from 377 to 955kPa) in BD, compaction index, shear strength, and soil tensile strength respectively under mechanized tillage. In addition, [34] reported low soil porosities under high tractor tire inflation pressures (0.17MPa) compared to machines with tracks and low-pressure tire systems (0.04MPa) under maize-cropped silt clay loams. Further, [35], reported a 17.9% increase in macropores under low tyre inflation pressures than that corresponding to standard tyre inflation pressures in tillage of silty clay loams.

Soil penetration resistance values greater than 2MPa changed maize rooting depth, growth, and yields with variable magnitudes [1], [36]. Penetrometer resistance of 3.0MPa was identified as the critical level of maize crop rooting and growth [37]. However, [38] reported 1.38MPa as the lowest machinery-induced compaction threshold for optimal maize growth. Because of dynamic soil limiting factors, other researchers have provided a cone index (CI) range of 1.5 to 3.0MPa as critical tillage machine-induced compaction limits maize growth [39]. According to [27], the average soil dry BD in the mechanized maize-growing region of central China was 1.38Mg/m^3 at 5cm depth and 1.52Mg/m^3 at the plow zone. A similar case was reported in the mechanized fields of Huang-Huai-Hai plain which produces over 30% of the country’s total yield [40]. However, [41] reported that 1.2Mg m^{-3} was the optimal BD for maize growth. Others have recommended a BD range of 1.2–1.3Mg/m^3 [42]. Researchers have consensually reported increased arable soil strength, BD, cone index, and maize root penetration impedance by machinery-induced compaction [43]. However, attributing mechanized tillage-induced compaction effects as soil type and soil depth-specific, further research is needed to quantify the most detrimental effect corresponding to a specific soil parameter in a maize-cropped soil-root environment.

3. Effect of Mechanized Tillage-induced Compaction on Maize Growth

Despite the benefits of improving maize productivity using conventional fertigation, mechanized tillage-induced compaction imparts physiochemical soil health, plant growth, and grain yield [44]. Although there are general impedance-educed shortcomings of compacted agricultural soils, researchers have reported multifaceted effects of tillage machine-induced compaction on the growth and yield of maize [45]. Mechanized tillage-induced compaction has been negatively correlated with maize growth and yields [46], [47]. However, no significant changes in crop growth were reported under tillage-induced compaction stresses due to the buoyance effects of soil pore water that reduced total downward stresses on soil particles [2].

3.1 Effect of mechanized tillage-induced compaction on maize root growth and architecture

Several researchers have studied the effect of tillage machine-induced compaction on maize root architecture, development, and traits [3], [27]. Mechanized tillage-induced compaction significantly affected the early stages of maize rooting architecture and growth [45]. It repressed root emergence, root establishment, and penetration into the soil [48], [49]. This was due to low soil oxygen diffusion attributed to high levels of soil strength as caused by mechanized tillage-induced compaction. Maize root growth rate, length, number of roots, function, and distribution were negatively impacted by high tire inflation pressure and axle load-induced compaction [50]. However, higher maize root mass and concentration were reported in the topsoil (0-10 cm); and less root extension in deeper layers (10-50cm) of mechanized compacted soils [40], [51], [52]. Tillage-induced compaction increased maize root diameters closer to the stem base, although lower root stiffness and anchorage were reported in lower-strength soils [53]. Soil machine-induced compaction was associated with stunted rooting and poor maize root proliferation [28]. It also affected the pattern of root distribution and decreased root elongation [51], [54]. According to [55], maize root structure, root length, and root volume were not significantly affected by mechanized tillage-induced compaction of soils with water contents at field capacity. Nonetheless, soil compaction by high tractor loads in tillage caused more transverse rooting and less maize root growth in the longitudinal directions with significant rooting intensity and volume in the topsoil layer (0–10 cm) than in deep (10–40 cm) layers [18].

Mechanized tillage-induced compaction suppressed maize root mass, accumulation, and density in the subsoils more than topsoils [56]. According to [57], shallower rooted architecture as indicated by the width, length, and opening angle of maize root crowns increased with mechanized tillage - induced compaction. Further, compaction-induced root impedance stresses weakened root elongation strength due to reduced cortical cell layers, central cylinder, and xylem vessel diameters [58]. Although root extension and growth were curvilinearly correlated with machine-induced penetration resistance, a more horizontal rooting direction with larger diameters was reported [59]. According to [60], there was no influence of tillage machine-induced compaction on the number of seminal and seminal adventitious maize roots. However, root lengths and total lengths of seminal and seminal adventitious roots decreased by 29% under severe (1.58 g cm^{3}) compaction levels, 49 days after seeding [61]. There was a decline in root numbers, root length density, and soil-root volume but with increasing diameter of lateral and axial maize roots in response to increased tillage-induced compaction [62]. Although tillage machine-induced compaction decreased the penetration capability of maize root apex, it intensified lateral root formation in the topsoil [63]. According to [64], mechanized tillage-induced compaction levels with a CI of 1.4 MPa increased BD to 1.6 g cm^{-3} and resulted in reduced root length density and root volume at the hardpan layer (20-30 cm depth). Moreover, tractor wheeling compaction stresses decreased maize root density by about 90 % at 30 cm depth [65]. Maize root mass was reduced with increased soil BD in maize-cropped compacted silt clays, loamy sand, and silt loam soils [66]. On the contrary, studies [67] reported that even though machine-induced compaction influenced root elongation rates, distribution, and diameter of maize roots, it did not affect fresh root weight. Although the increased diameter of the fine roots increased linearly with the average diameter of the main roots that was congruent with compaction levels, root depth, and mass declined with machine-induced compaction and root penetration impedance [68].

Mechanized tillage-induced compaction does not always affect maize cropping parameters. Tillage-induced compaction of topsoils (0-30cm) had the highest maize root mass (over 50%) although it drastically declined (to 10%) at subsoil depths (30-40cm) as reported [56]. Further, mechanized tillage-induced compaction consolidated the surface tilth and enhanced soil-seed contact, soil-root contact, root-soil bond, and nutrient contact reach [1], [46]. It also improved the root lodging resistance of maize at the compact wheel tracks [69]. Moreover, mechanized tillage-induced compaction enhanced maize root anchorage, root-soil bond, and root lodging resistance that outweighed the negative influence of reduced root growth, distribution and nutrient absorption [70]. According to [43] hydration or matric potential of a given soil, texture affects penetration resistance whose effect on mechanical bioturbation energetics influences root elongation rates in mechanized tillage-induced compaction. As such the effect of tillage-induced compaction on root penetration and elongation would be much less in compacted wet soils with higher BD and low aeration. Nonetheless, tillage-induced compaction retarded root elongation rate, root length, root depth and branching density, and water/nutrients exploitable soil-root volume. There exist inconsistencies in root response to mechanized tillage-induced compaction, partially blamed on indirect influence from soil water stress levels. As such, the knowledge of the least limiting water range and at what levels of tillage machine-induced compaction would deter root development and yield need to be subjected to further studies.

3.2 Effect of tillage machine-induced compaction on maize root water extraction

A decline in root water extraction has been reported as a consequence rather than a cause of reduced plant growth under compacted clay loams where maize root density limited root water uptake [71]. Water extraction was more correlated to the crop rooting patterns than tillage-induced penetration resistance at the compacted zones although water retention characteristics influenced general root ontogenesis [72]. Moreover, maize root density and root water uptake in machine-induced compacted clay loams were both associated with reduced water extraction that correlated with reduced crop growth [71]. This shows that soil mechanical impedance restricted maize root extraction of soil-bound water. In contrast, [42] reported the highest and lowest water uptake under intermediate and lowly compacted soils respectively. As such, water uptake per unit of root length decreased with machine-induced compaction and declining soil-root contact in uncompacted soils [37]. This was perhaps because tillage machine-induced compaction improved the duration of water ponding in soils and enhanced its availability to maize roots. Moreover, mechanized tillage compaction of topsoils affected only soil water content and did not significantly affect maize growth and productivity [73], [74]. According to [60], tillage-induced compaction enhanced the uptake of available topsoil water leading to a further increase in soil strength due to top-layer water depletion, the vicious cycle of mechanized soil compaction. Moderate compaction reduced water loss from the soil through evaporation and retained water around the seed thus improving maize germination rate due to better soil-water-soil-seed contacts [75].

Researchers have reported significant effects of machinery-induced compaction on maize root access to available soil water [51], [54]. Even though compacted soils may still contain water, it becomes unavailable to maize roots as it is greatly and tightly held in tiny micropores [76]. However, the mesopores responsible for short and long-term retention of soil moisture could still hold soil water against the force of gravity in mechanized compacted soils [29]. Nonetheless, machine-induced compaction restricted maize root access to readily available water pools as it affected soil pore numbers, total soil porosity, and infiltration rate [64]. According to [77], high soil water podding above the impenetrable machine induced plow pan layer recanted maize root aeration and accelerated anaerobic environment that restricted nutrient uptake. There have been contrasting results as to the basis and effects of maize water and nutrient uptake and whether solely caused by tillage machine-induced compaction directly or not. For instance, [37] there was an increase in root water uptake in soils with moderate machine-induced compaction (BD of 1.5 Mg m^{-3}). Mechanized tillage-induced compaction at the topsoil led to an improved soil-root density of the shallow-rooted architecture that increased the rate and intensity of maize water uptake [78], [54]. However, such effects increased topsoil drying and restrained maize root growth into deeper layers, thus reducing water access and nutrient uptake from subsoil layers [4], [79]. Nonetheless and hitherto the constrained effects of maize root penetration resistance, the most immediate consequence of mechanized tillage-induced compaction is decreased water and nutrient use efficiency [80].

3.3 Effect of tillage machine-induced compaction on maize nutrient availability and uptake

Mechanized tillage-induced compaction affected nutrient availability, concentration, transformation, diffusion, absorption, uptake, and transport [32], [73], [81]. According to [82], nutrient transport restrictions by mechanized tillage-induced compaction were dependent on available water and levels of applied nutrients. As such tillage machine-induced compaction did not affect the concentration, diffusion, and mass transport of ions in fertile well-watered soils due to greater hydraulic conductivity and water retention [83]. Nonetheless, above certain limits, increased machine-induced compaction and soil BD reduced the diffusion coefficients of ions due to increased pore tortuosity and root penetration impedance [84]. Specifically, reduction in the maize root absorption levels of nitrogen (N), potassium (K), magnesium (Mg), and sodium (Na) by 13.5%, 51.4%, 50.4%, and 51.5% were respectively observed when soil CI was increased from 1.5 to 5.2MPa [85]. In contrast, machine-induced compaction enhanced nitrogen utilization due to increased soil-root contact with a greater proportion of fine roots, especially at the seedling stages of maize [86].

3.3.1 Mechanized tillage-induced compaction on maize nitrogen uptake.

Nitrogen imbalances have been reported due to machine-induced compaction. Tillage-induced compaction led to soil aeration alterations that contributed to denitrification, gaseous nitrogen losses, and N demineralization [87]. Tillage machine-induced compaction stresses above 540 kPa decreased the efficiency of maize root N uptake due to reduced total organic N content of maize-cropped soils and gaseous N losses [88]. Further, induced compaction-related alterations of soil particle arrangement and soil-root contact resulted in reduced N uptake, transport and leaching, and ion diffusivity [89]. Restrained N uptake significantly affected the total growth compared to the levels of machine-induced compaction [90]. However, [91] reported that tillage machine-induced compaction had the greatest maize growth suppression effects compared to N uptake and fertilizer placement depth. In retrospect, N fertigation compensated for machine-induced compaction effects by enhancing maize root growth in zones of favorable N supply [92]. As such maize N uptake was highest under moderate tillage machine-induced compaction and slightly lower under non-compacted (porous) soils [59]. This was also evidenced by diminishing N uptake per unit root length with increased compaction levels [87]. As such, reduced soil macropores and available oxygen in tillage-induced compaction decreased the rate of root activity and increased denitrification rates that diminished the N uptake of maize [88].

3.3.2 *Effect of mechanized tillage induced compaction on maize Phosphorus uptake.*

The effect of mechanized tillage-induced compaction on maize uptake of P was related to the configuration of the root systems because of its relative immobility. Generally, machine-induced compaction was associated with low accessibility and total uptake of P [82]. However, the uptake of P per unit root length was greater in compacted soils while P uptake restrictions were easily counterbalanced by root overgrowth [31]. However, such compensatory capacities albeit relied on the positive influence of higher water availability [89].

3.3.3 *Effect of mechanized tillage-induced compaction on maize potassium uptake.*

Mechanized tillage-induced compaction restricted the respiratory capacity of maize roots thus reducing their ability to develop the energy required for active uptake of K [46]. Moreover, high soil bulk densities in mechanized tillage limited the diffusion properties of K by altering its characteristic ionic pathway [72]. However, K uptake was most restrained compared to N while P was the least affected by mechanized tillage-induced compaction [91]. Further, contrasting studies reported that machinery-induced soil compaction greatly reduced P uptake with no effect on N uptake [89]. There was a positive effect of P on maize root mass and diameter while shoot growth was limited in tillage-induced compaction [67]. Moreover, increased P levels led to increased limitation of K at higher compaction levels [93]. Although conventional K nutrition may improve maize yields in tillage-induced compacted soils, such improvements and their level of significance vis-à-vis available tillage-induced compaction alleviation methodologies need to be quantified by further research.

3.4 Mechanized Tillage-induced Compaction and Morphological Functioning of Maize

Mechanized tillage-induced compaction exhibited shriveled morphological and physiological dysfunctionalities of maize [37]. Mechanized tillage-induced compaction reduced the growth and development of maize due to a decline in leaf functions, stomatal conductance (g_s), and photosynthetic rates [94]. It reduced leaf expansion, stomatal activities, and yield quality [95]. According to [56], transpiration intensity (E), leaf water potential (ψ), and g_s, photosynthetic rates decreased significantly at midday (12:00hrs) and 16:00hrs in tillage-induced compaction compared to uncompacted lands. Moreover, tillage machine-induced compaction hampered the relative chlorophyll index, gaseous exchange, and leaf water status [96]. This is because ψ and photosynthetic efficiency change with internal concentration of carbon dioxide was responsible for g_s and behavior in compacted maize-cropped soils [97]. Corroborative, tillage machine-induced compaction reduced g_s, E, and net photosynthetic rate; whilst maize leaf stomatal density negatively correlated with both net photosynthetic rate and leaf E, but more significant with E [98]. Such drawbacks were associated with poor root growth and insufficient root turgor build-up to push the side soil due to high machine-induced compaction [99], [100]. In contrast, tillage-induced compaction did not affect ψ of maize grown in a compacted plow layer (at 0-30cm depth) with a BD of 1.3-1.5g cm^{-3} [101]. [102] revealed that any changes in maize ψ under moderate to severe tillage-induced compaction were like those of plants exposed to actual soil drought stress. Such stresses prompted stomatal closures and were intimately linked to slowed transpiration due to decreased ψ in mechanized compacted soils [103]. However, [104] reported a significant decline in the photosynthetic rate of maize grown under mechanized tillage with an ample supply of water. Prompt stomatal closures by machine-induced compaction-related stresses led to reduced carbon assimilation rates and photosynthetic feedback mechanisms of maize [105]. Whilst soil water content did not limit maize leaf water status, researchers could intrinsically attribute reduced photosynthetic rate to compaction-related limitation of soil-pore-root aeration [50].

Mechanized tillage-induced compaction of arable soils led to decreased leaf gaseous exchange, carbon assimilation, and transportation of photosynthates thus retarding maize growth [5]. This is because a reduction of soil porosity and aeration due to compaction from heavy tillage machinery caused a decline in soil-root zone oxygen levels, soil-root activity, and growth morphologies [106]. It also reduced the vegetative growth rate and decreased the green biomass, regenerative development, and flowering vigor, which were congruent with photosynthetic rates [107]. Although air-filled porosity of $0.1m^{-3}m^{-3}$ and penetrometer resistance of 2MPa were regarded as critical values, they did not completely inhibit but only slowed down the maize growth rate in soils with a wide range of texture class and organic matter content [108].

4. Effect of Mechanized Tillage-induced Compaction on Maize Biomass and Grain Yield

4.1 Tillage-induced compaction and maize biomass

Compared to root traits, the effect of mechanized tillage-induced compaction on maize was more pronounced on shoot characteristics [75]. Maize vegetative development declined with increased tillage machine-induced compaction [19]. Amassed evidence associated tillage machine-induced compaction with stunted shoot, reduced stem length, stem girth, leaf area, stem diameters, and plant height [48], [109]. According to [110], annual tractor-tire-induced compaction in tillage led to a 21% and 11% reduction in maize plant height after 42 days of planting and at harvest respectively. Further, maize height declined by 10% after increasing the tractor-tire load on the soil by 19 Mg in the first year of tillage [111]. [66] reported that machinery-induced compaction did not affect the growth height of maize in silty clay loam, Plainfield loamy sand, and Plano silt loam soils. However, shoot elongation and leaf area declined significantly ($P<0.05$) by 27.1% and 67.8% respectively at high compaction levels [85].

Fresh and dry root biomass of maize decreased significantly ($P<0.05$) by 39.1% and 37.8% although shoot elongation and leaf area declined by 27.1% and 67.8% respectively at high compaction levels [85]. Although shoot biomass declined, maize shoots fresh weights per unit root length decreased with increasing tillage-induced compaction [59]. Further, compaction from high tire inflation pressures in mechanized tillage led to declines in the number of maize shoots and plant population [110].

4.2 Mechanized tillage-induced compaction and maize grain yield

Researchers have conducted short-term and long-term studies aimed at characterizing maize biomass and grain yield from tillage-induced compacted soils [19], [82], [73]. Significant reductions in maize yields have been reported under severe tillage-induced compaction [80], [47]. Maize crop vigor is responsible for maize grain mass yield (GMY) but it declined with increased tillage-induced compaction [19], [112], [113]. For instance, [114] reported a reduction of maize yields by 4.13% and 2.62% in the 2nd and 3rd years respectively, due to mechanized tillage-induced compaction by tractor tires. Severe tillage machine-induced compaction led to a 50% decline in maize GMY [13], [115]. However, [85] reported an 18% yield decline while [116] reported a 10 -15% decline in GMY due to tillage machine-induced compaction. On average, tillage machine-induced compaction decreased the maize GMY by 34% in medium-textured soils and by 15% in fine-textured soils [19]. Although there was no effect on grain yield from mechanized tillage-induced compacted clays [2], there was a 50% reduction in grain yield in heavily mechanized compacted sandy loams [106] and both clays and loams [75]. [117] reported a decline of maize yield by 18% for every 0.1 Mg m^{-3} increase in BD above 1.3 Mg m^{-3} in tillage-induced compacted soils with 30–40% clay content.

Mechanized tillage yield simulation models predicted a 23 to 30% maize grain yield reduction under all axle loads of tillage machinery [118]. In contrast, [119, 108] reported higher maize grain yield due to improved soil-root contact in moderate tillage-induced compaction compared to uncompacted soils. Mechanized tillage-induced compaction did not significantly deter maize yields because soil texture, organic matter, limiting water range, and clay mineralogy counteracted crop rooting and nutrient uptake severities with time [120], [121]. Such inconsistencies in the effect of tillage-induced compaction on the overall growth and yield of maize could partly be attributed to the influence of other soil dynamic actors and environmental covariates [43].

The susceptibility of maize yields to the critical effects, levels, and limits of mechanized tillage-induced compaction levels is still debated. Researchers have not corroborated the critical level of mechanized tillage-induced compaction that would significantly reduce maize yields without the effects of other soil, environmental conditions, or nutrient status. Further research is needed to demystify the influence of other dynamic actors such as soil structure, moisture levels, and organic matter content in counteracting the effect of mechanized tillage-induced compaction levels on maize yield.

5. Remediation Benefits of Mechanized Tillage-induced Compaction

Some of the researchers suggested low tillage machine axle loads and low tire inflation pressures [122]) while others recommended regular subsoiling, strip tillage, and controlled traffic [115] to control mechanized tillage-induced compaction. Others have suggested conservation tillage, organic matter sequestration [123], and bioturbation [28]. The inclusion of deep tap-rooted crop species in rotation programs has also been reported to reduce the detrimental effects of tillage machine-induced compaction on maize [52]. For instance, under alfalfa-maize rotation, 41% of the total maize root mass was colonized in root-induced channels and macropores of alfalfa and only 18% when following maize monoculture [124]. Moreover, [48], commended dicot-monocot rotation because dicots penetrated compacted soils (about 58% of roots) better than maize (only 33-36% of the roots). However, [110] reported that deep tillage strategies improved maize yields by 17% after one year of compaction abandonment; although were lost if followed by heavy tillage machinery in subsequent years.

According to [1] and [39], once machine-induced compaction has reached the deep subsoil layers, permanent compaction stay may ensue a claim that requires further scientific inquiry. According to [39], tillage machine-induced compaction impacts are long-term and do not respond quickly to self-correction as shown in Figure 3.

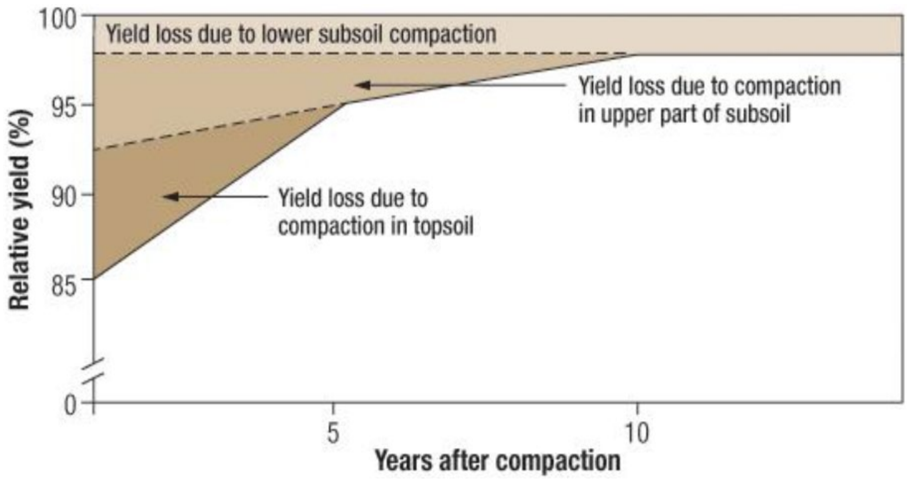

Fig. 3. Maize yield over time in compacted top and subsoil (upper and lower) layers. Adapted from [39]

While averaging the problematic situation across all the soil profiles under maize crop roots, deep strip tillage best decreased the deleterious effects of tillage machinery-induced compaction on maize growth and yield [125], [27]. However, further investigations are required to furnish the most sustainable and soil-specific remediation techniques for compaction-susceptible agricultural soils under mechanized tillage routines in maize cropping.

6. Conclusion

Mechanized tillage-induced compaction is mainly caused by tractor wheeling and high axle loads. Although maize thrives in diverse soil types, sandy and coarse-textured soils are less prone to mechanized tillage-induced compaction and its effects compared to finer clayey soils. Mechanized tillage-induced compaction results in impaired maize root establishment, water, and nutrient uptake, and reduced crop growth and grain yield. However, there exists contrasting and multifaceted feedback where mechanized tillage-induced compaction favored some maize crop traits (soil-seed contact, root mass, root diameter, soil-root contact, stiffness and anchorage, soil-root density, soil-root bond, and root lodging resistance). Nonetheless, no single acting or independent mechanized tillage-induced compaction effect on soil root environment would significantly limit a specific maize cropping trait without drawing positive or negative influence from other soil parameters.

A tripartite approach and investigations that encompass integrated aspects viz soil biochemical properties by soil scientists, crop husbandry and management by agronomists, and physicomechanical parameters by agricultural engineers are required to redress the effects of mechanized tillage-induced compaction on maize growth and yield. Further, most of the studies investigated a single attribute of tillage machines on the induced compaction effects on crop growth i.e., either, axle load or tire inflation pressure, or number of machine pass in one soil type and same climatic region. This limits the robustness of conclusions from such studies. The effects of mechanized tillage-induced compaction on maize growth and yield are dependent on various integrated dynamics such as changing moisture regimes with organic matter content, soil texture, soil-root gaseous diffusion, or limiting water range with time and climatic conditions. Nonetheless, conditioning the soil for maize root penetration and development is the primary approach for improving the yield.

TABLE 1. Summary of mechanized tillage-induced compaction on maize-cropped soil-root environment, growth, and yield

Parameter(s) Studied	Location(s) and Soil Information	Effect(s) of Mechanized Tillage-induced Compaction	Key References
a) Soil ecological properties, BD, RG, CG	(i) Brazilian subtropical soils (ii) Kenyan luvisols	(i) High soil mechanized induced soil compaction did not restrict RG and crop yield because soil texture, limiting water range, organic matter content, clay mineralogy, and the tillage system plays a key role. (ii) Ecological properties of compacting maize-cropped soil root system viz microporosity, aeration, and hydraulic conductivities are first affected by compaction before CG and yield restrictions ensue.	[120], [121]
b) PR, CG, Water uptake, Root mass, and root architecture	(iii) Zurich, Switzerland, Loamy textured soil (iv) Fine, coarse, and medium-textured soils	(iii) High PR increased root water uptake from the topsoil leading to soil drying and further increasing the topsoil PR. (iv) Reduced RG into deeper soil layers while CG decreased with tillage-induced compaction. (v) Shallower maize root architecture increased with soil PR and mechanized tillage-induced compaction levels. On average, mechanized tillage-induced compaction increased PR of fine-textured, coarse, and medium-textured soils by 41, 94, and 99% respectively.	[60], [57], [19]
c) CG, RDM, LA, Crop productivity, d) Nutrient uptake and yield.	(v) Ondo state, Nigeria; Sandy clay loam	(vi) Shoot elongation and LA decreased significantly (by 27.1 and 67.8% respectively) at PR ($P<0.05$). (vii) Fresh and RDM decreased significantly (by 39.1 and 37.8% respectively). at high PR. (viii) An increase in PR reduced nutrient uptake by 13.5%, 50.4%, 51.4%, and 51.5% for N, Mg, K, and Na respectively. (ix) RG, shoot elongation, root biomass, Nutrient uptake, and GMY declined with an increased PR in mechanized tillage-induced compaction.	[85], [126]
e) RG, PR, TRL, Root water extraction, and N uptake	(vi) Iowa, USA. Clarion soil (loamy, mixed, mesic, Typic Hapludolls) (vii) Agricultural soils	(x) Mechanized tillage-induced compaction had a more significant effect on N uptake compared to TRL. (xi) Nitrogen fertigation greatly increased N uptake when compaction zones were present than not. (xii) Root water extraction in compacted soils was directly related to root density and PR levels. (xiii) Tillage-induced compaction renders soil water unavailable to maize roots as it is greatly and tightly held in tiny micropores.	[76], [90]

Parameter(s) Studied	Location(s) and Soil Information	Effect(s) of Mechanized Tillage-induced Compaction	Key References
f) BD, root and shoot mass, maize height	(viii) Silty clay loams, Plainfield loamy sands, and Plano silt loams of Wisconsin Kewaunee (ix) Loamy soil, silt-sandy loam and peat, and sandy soils of Poland	(xiv) Mechanized tillage-induced compaction enhanced maize root mass accumulation in the topsoils than subsoils respectively. (xv) Mechanized tillage-induced compaction of topsoils (0-30cm) had the highest maize root mass (over 50%). (xvi) Over 50% of root mass accumulated at the topsoil (0-30cm) but declined up to 10% in the subsoil depth (30-40cm) of mechanized compacted soil.	[66], [56]
g) BD, *Ψ,* RG, PN, and E	(x) Poland; Garden soil at 1.10, 1.34, and 1.58 Mg/m^{-3} bulk densities (xi) Sandy clay loam texture ultisol	(xvii) Mechanized tillage-induced compaction restricted RG and reduced ψ, PN, and E in maize leaves. (xviii) Tillage machine-induced compaction hampered relative chlorophyll index, gaseous exchange, and leaf water status.	[50], [96]
h) Leaf number, Stem, leaf, and root mass Shoot to root ratio and RB, Root traits	(xii) Poland and Slovakian soils under Low, moderate, and severe compaction levels (xiii) Clay loams of Henan province, China	(xix) Leaf number, dry mass of stem, leaves, and roots decreased under M or S treatments in comparison to treatment L, and an increase in the shoot-to-root ratio. (xx) Soil compaction levels did not influence the number of seminal and seminal-adventitious maize roots but decreased their length. (xxi) The number and nodal roots and their total lengths decreased with compaction. (xxii) Tillage-induced compaction let to high maize root mass and concentration in the topsoil (0-10 cm); and less root extension in deeper layers (10-50cm).	[56], [40]
i) Maize Yield (%)	(xiv) Pennsylvania; Silt loam, (xv) Federal University of Technology, Nigeria (xvi) Medium and fine-textured soils	(xxiii) Mechanized tillage-induced compaction effects reduced maize yield by 17% from the 3rd year of tillage. (xxiv) Tillage-induced compaction reduced the grain yield by 18.8%. (xxv) On average, tillage machine-induced compaction decreased the maize GMY by 34% and 15% in medium and fine-textured soils respectively. (xxvi) Severe mechanized tillage-induced compaction led to a 50% decline in maize GMY.	[110], [85], [19] [13], [115]

TIP tire inflation pressure, *CT* Conventional tillage, *DM* Dry Mass, *BD* Bulk density, *PR* penetration resistance, *RG* root growth, *CG* crop growth, *ψ* Leaf water potential, *PN* photosynthetic rate, *E* intensity/rate of transpiration, *CE* Carbon exchange, *LT* leaf transpiration, *PT* plant transpiration, *LA* leaf area, *LDW* leaf dry weight, *SDM* shoot dry mass, *TRL* total rooting length, *RSA* root surface area and *RDM* root dry mass.

7. Conclusion

Mechanized tillage-induced compaction is mainly caused by tractor wheeling and high axle loads. Although maize thrives in diverse soil types, sandy and coarse-textured soils are less prone to mechanized tillage-induced compaction and its effects compared to finer clayey soils. Mechanized tillage-induced compaction results in impaired maize root establishment, water, and nutrient uptake, and reduced crop growth and grain yield. However, there exists contrasting and multifaceted feedback where mechanized tillage-induced compaction favored some maize crop traits (soil-seed contact, root mass, root diameter, soil-root contact, stiffness and anchorage, soil-root density, soil-root bond, and root lodging resistance). Nonetheless, no single acting or independent mechanized tillage-induced compaction effect on soil root environment would significantly limit a specific maize cropping trait without drawing positive or negative influence from other soil parameters. Thus, a tripartite investigation encompassing soil biochemical properties by soil scientists, crop husbandry and management by agronomists, and soil physicomechanical parameters by agricultural engineers' approach is required to redress the effects of mechanized tillage-induced compaction on maize growth and yield. Further, most of the studies investigated a single attribute of tillage machines on the induced compaction effects on crop growth i.e., either, axle load or tire inflation pressure, or number of machine pass in one soil type and same climatic region. This limits the robustness of conclusions from such studies. The effects of mechanized tillage-induced compaction on maize growth and yield are dependent on various integrated dynamics such as changing moisture regimes with organic matter content, soil texture, soil-root gaseous diffusion, or limiting water range with time and climatic conditions. Nonetheless, conditioning the soil for maize root penetration and development is the primary approach for improving the yield.

8. Recommendations for Further Research

The constitutive range of soil-maize crop response to mechanized tillage-induced compaction levels under various soil types whose, effects emanate from tire inflation pressures or axle loads need to be investigated further. The knowledge of maize root penetration impedance limits and reference bulk densities for various soil loading levels from tillage machinery under respective soil ecological properties is still scanty. Tillage machine loading stresses and associated compaction limits need to be established for various soils and maize varieties and be published as standard manuals to guide tillage operations. Studies aimed at mitigating adverse effects of tillage machine-induced compaction to optimize soil-root interactions and improve crop nutrient cycling and absorption, while unbundling their level of significance are imperative.

Allowable soil-wheel stress limits and tillage machine axle loads that would constitute what levels of maize growth and yield declines for numerous maize varieties under various soil-root environments are still lacking. We recommend studies on maize root tolerance and the development of compaction compaction-resilient root cultivar genotypes that are adaptable to compacted soil-root environments. Further research is required to establish the influence and levels of significance of dynamic actors such as soil moisture and organic matter content in counteracting the negative effects of tillage-induced compaction on maize growth and yield. Thus, modeling the response of maize growth and yield under tillage-induced compaction variabilities would decisively support the implementation of site-specific tillage for ameliorating the effect of machine-induced compaction under modern mechanized agriculture. The review forms a basis for future studies focusing on an optimized physio-mechanical soil-root environment for improved maize yields under the changing climate.

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