Effects of soil-tool interaction and mechanical pulverization of arable soils in tillage - a comprehensive review

Frankline Muriungi Mwiti[1,2*], Ayub Njoroge Gitau[2], Duncan Onyango Mbuge[2]

(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)

Abstract: Tillage tool designers focus on draft forces and energy requirements in evaluating tillage performance, while field-scale users consider the qualities of the resultant tillage finish as the most pertinent parameters. Due to these counterpointed approaches, we reviewed soil-tool interactions and mechanical pulverization to guide the design and performance evaluation parameters for newly developed tillage tools.Soil-tool interface characteristics influenced pulverization and deformation behavior of arable soils. While cohesionless soils caused segregation and flow failure, the cohesive and adhesive types crumbled at higher specific drafts. Failure patterns, soil-layer mixing, and loosened areas were majorly affected by tool width/depth ratio and rake angles compared to speed. Dependent on tool speed over depth, soil disturbance, throw and pulverization intensities were optimized at 25 °-30 °rake angles. However, tool depth had the greatest influence on draft forces than speed and rake angles.

Varying the tooling geometries affected pulverization intensity, deformation, and tillage draft by as high as 20%-50%. Winged tine geometries increased disturbed areas by 50%, although at 30% higher draft compared to rectangular, triangular, and trapezoidal tines. Concave tools improved soil-residue mixing by 20.7% at 20% less draft compared to flat-rectangular tines. Combined active-rotary tools increased soil pulverization modulus and improved residue incorporation (by 30%), operational timeliness (55%-61%), tillage index (0.94-1.26), and fuel efficiency by 34%, compared to single-acting passive tools.In-depth studies of soil-engaged failure front are required to constitute field-scale models that integrate the tillage finish properties with draft, fuel consumption, and operational timeliness for defining the overall performance of tillage tools.

Keywords: soil failure, tool geometry, draft force, rake angle, tillage tool design, tillage modeling

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1 Introduction

Soil-tool interactions affect the physicomechanical properties of agricultural soils upon tillage. Deformations at the soil-tool interface influence failure front patterns, tilled surface profile, clod size and distribution, aggregate orientation, and the resultant tillage finish (Usaborisut and Prasertkan, 2019). These parameters affect the subsequent soil-root interactions. However, tillage tools and implement designers parametrize tillage performance and quality by considering tillage energy, draft requirements, and the magnitude of propagated forces (Bögel et al., 2016). Tool designers have majorly focused on quantifying tillage forces and specific

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[1]**Corresponding author: Frankline. M. Mwiti,** Lecturer of Mechanization, Power and Machinery Engineering., Department of Agricultural and Biosystems Engineering, University of Eldoret, Kenya. Email: franklinemwiti2@gmail.com.

draft requirements at the lowest possible energy to qualify tillage performance (Usaborisut and Prasertkan, 2018; Abbaspour-Gilandeh et al., 2020). In contrast, there has been little attention on crop-oriented soil working, desirable soil manipulation, and qualities of the resultant tillage finish. As such, desirable crop-oriented soil-tool interactions have not been sufficiently furnished and adopted to evaluate tillage performance (Dekemati et al., 2019). Moreover, some of the soil-tool interaction parameters such as the width of cut and advancing tool speed have assumptively been developed in a quasi-static condition of the soil-tool-system under controlled experiments of indoor artificial soil bins (Wang et al., 2022). This ignored the complex rheological and dynamic soil reaction behavior at the soil-tool interface in situ (Odey et al., 2018; Ajayi et al., 2020). As such, field-scale effects of soil deformation behavior, and mechanical pulverization characteristics that parametrize overall tillage quality and performance have not been adequately constituted. Moreover, many of the available studies have only been conducted on a few parameters, such as draft force, tillage energy, and fuel consumption of respective tillage tools to define tillage performance (Ajayi et al., 2020; Makange et al., 2021). However, optimizing qualitative tillage performance of the designed tools requires accurately integrated characterization of soil-tool interactions, soil-tool-force response behavior with the resultant tillage finish (Tesfahunegn and Gebru, 2020). This review provides information on the interactive effects of the soil-tool nexus and a reference for improving the design and performance evaluation of newly designed tillage tools. It guides the tool and implement developers on improving soil working characteristics and provides field scale users with a wide range of optimized designs that achieve their desired tillage quality and performance.

2 Soil-tool interaction in tillage

Soil-tool interaction is a dynamic action of soil failure front ahead of the soil-engaging tool at the soil-tool interface (Milkevych et al., 2018; Schramm et al., 2020). Soil-tool interactions occur under distinctly variable, site-specific soil characteristics across and within the field discontinuities (Tesfahunegn and Gebru, 2020). As such tillage tools combat complex, spatial-temporal variations, and heterogeneous characteristics of the soil matrix. Consequently, due to instantaneously changing soil resistances, the tool-engaged soil en masse utilizes variable and momentary draft forces from the combating forces of tillage tools (Guan et al., 2021). Further, the soil-tool interface encounters variable and point-specific soil deformation and failure behavior due to variable soil adhesion, cohesion, and frictional forces within the heterogeneous soils (Ucgul and Saunders, 2020). Thus, the interaction of tillage tools with heterogenous physicomechanical soil states portends sophisticated stress relations, rendering the interaction mechanism as non-uniform and site-specific with complex multivariate nonlinearities (Massah et al., 2020). In addition, such multivariate complexities render the soil-tooling process into a complete sweep and pulverization action by the available tillage tool geometries (Ucgul and Saunders, 2020). This confines the design and development of desirable soil-tooling geometries that would adequately support the qualitative functioning of the resultant tillage finish, and the edaphic soil-root environment (Mwiti et al., 2022).

2.1 Intrinsic properties of soil-tool interactions

Implement configurations, tool geometry, operational settings, and initial soil conditions were considered as firsthand parameters for evaluating the characteristics of soil-tool interactions (Hoseinian et al., 2022a). On the other hand, the intensities of cut, soil inversion, soil movement, and pulverization were associated with the resultant action of soil deformation and failure (Barr et al., 2018). Further, the output of soil-tool interactions such as soil reaction stresses, soil response behavior, and multi-dimensionally transmitted forces were pertinent considerations for soil-tool interactions (Da Rocha et al., 2016). The critical depth, resultant furrow profiles, vertical soil layer mixing, draughts force requirements, and vertical soil reactions were regarded as pertinent parameters for evaluating soil-tool interaction (Solhjou et al., 2012). Furrow cross-section area, furrow tilth, and effective depth were reported as important characteristics for describing soil-tool interactions and disturbance (Conte et al., 2011). Moreover, soil failure mechanisms, lateral soil throws, critical depth of failure zone, residue burial, and surface failure profiles and their roughness indices were used in the evaluation of soil-tool interactions (Barr et al., 2018). Some of the parameters for evaluating soil-tool interactions are shown in Figure 1.

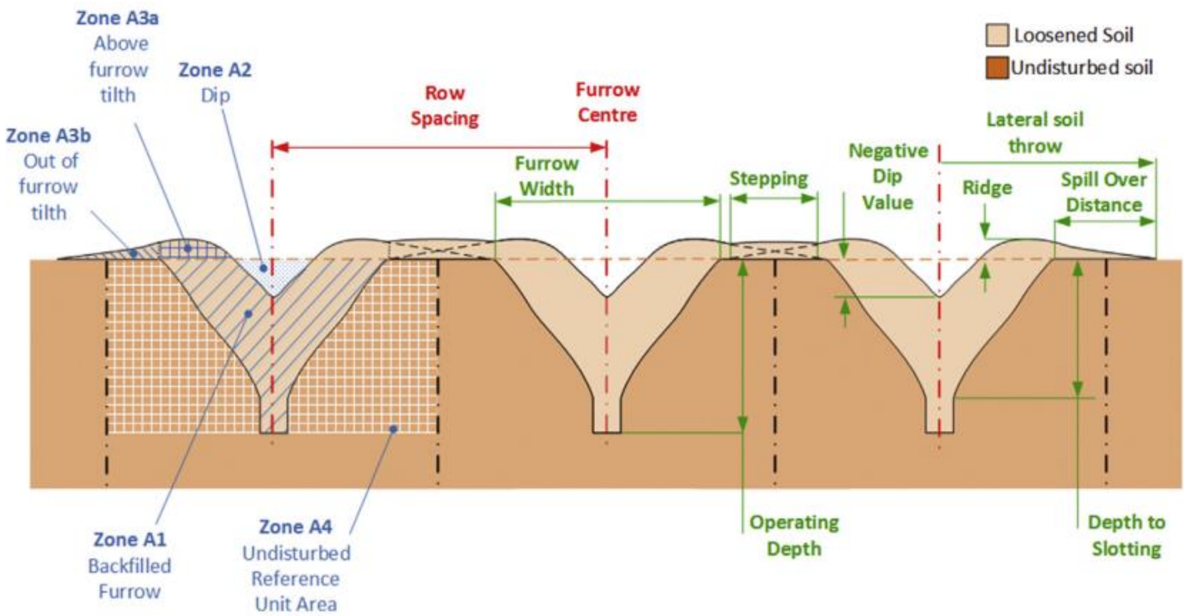

Figure 1 Soil-tool interaction parameters for tine openers (Barr et al., 2018)

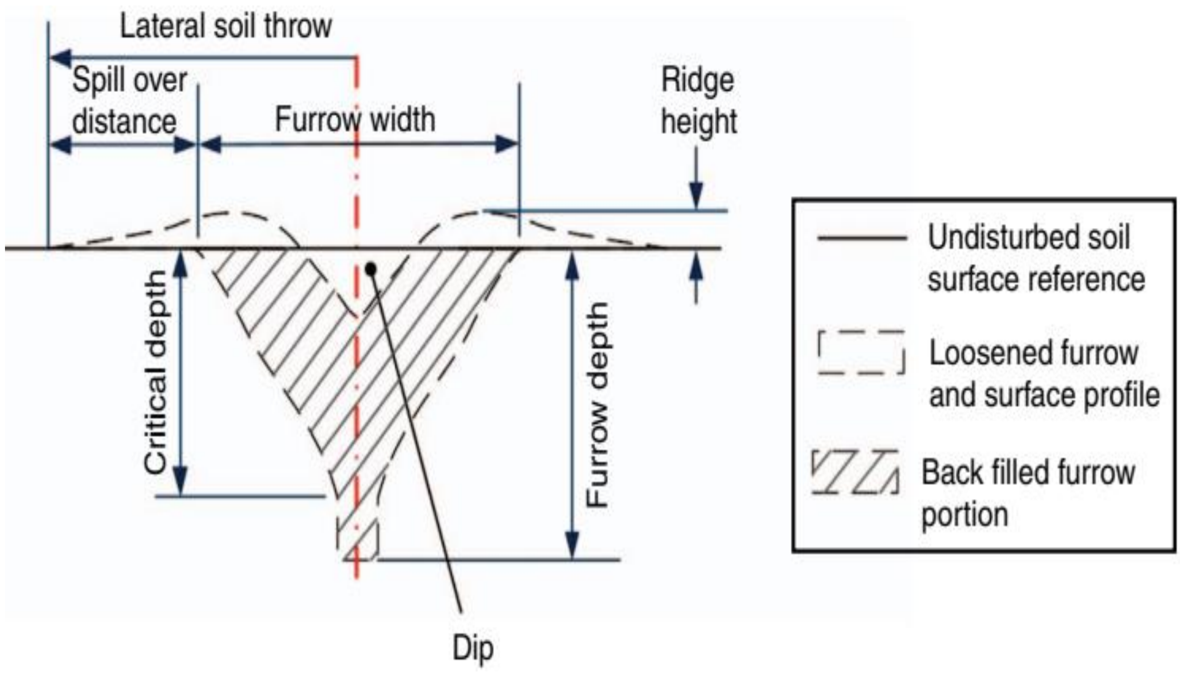

Figure 2 Soil-tool interaction and disturbance parameters (Aikins et al., 2020)

Some of the researchers reported rake angles and tool depth as the most fundamental soil tooling parameters that had been established and recognized as indicators of the degree of soil-tool interaction and soil disturbance (Solhjou et al., 2012). Other researchers reported tillage energy and utilized draft forces as the most significant parameters for evaluating soil-tool interactions and tillage performance (Fechete-Tutunaru et al., 2019). According to Solhjou et al. (2012) furrow backfills, and the proportion of loosened areas were important parameters for evaluating the deformative action of soil-tool interactions. On the other hand, Zhang et al. (2016) considered the width of soil throw, ridge-to-ridge distance, disturbed soil area, ridge height, and furrow cross-sectional areas for defining soil-tool interaction and soil disturbance as shown in Figure 2. However, the deformative action of soil-tool interactions around the tillage tool under the widely varying soil physical-mechanical properties, dynamic failure mechanisms, and associated failure front patterns are sparsely quantified. As such accurate knowledge of soil-specific parameters that would constitute what levels of soil disturbance and tillage quality need to be established and quantified to guide the design of tillage tools.

2.1.1 Soil-tool interactions and deformation mechanism

The mechanistic behavior that constitutes the deformation of soil encompassed cutting and multi-dimensional loosening, movement, displacement, and mixing of soil particles by induced soil-tool and soil-soil reaction forces (Wang et al., 2022). In effect, the deformative actions of soil-tool interactions caused soil cracking, breaking, churning, rutting, inversion, loosening, removal, displacement, and soil-residue mixing and hair-pinning (Hoseinian et al., 2022a). Although soil layer mixing was induced in the vertical orientation (Barr et al., 2016), soil displacement and movements took place in the forward and lateral directions within and from furrow profiles (Conte et al., 2011). Deformations of soil-tool interactions impacted soil structure, texture, strength, cone index, cohesion, adhesion, bulk density, porosity, and water-holding capacity of pulverized soils (Odey et al., 2018). Moreover, soil deformations disrupted ecological traits, biological activities, and soil-root morphologies of arable soils (Mwiti et al., 2022; Huang et al., 2020).

The magnitude and complexity of soil deformation, loosening, soil flows, and failure patterns were variably associated with the action of different tool parameters and soil properties (Karmakar et al., 2007). Although the widths of cut and width of soil throw, rupture distance, and ridge-to-ridge distances, increased with the variations of tine widths (10 to 200 mm) and moisture content (from 6.0% to 17.5%), the ridge heights of disturbed soils did not exhibit any trend (Manuwa, 2009). Deformative disturbance and soil looseness coefficients of soils while interacting with subsoiler shovel increased by 64.05% and 24.46% compared to spiral subsoilers (Li et al., 2019). However, soil failure and fragmentation to the desired tilth were more associated with a combined effect of soil-soil interaction, soil-tool interaction, and the entire tillage tool-implement configuration parameters (Karmakar and Kushwaha, 2005). On the other hand, topsoil burial received the greatest effect of force response reaction compared to forward failure and lateral soil movement in moldboard tool geometries (Ucgul et al., 2017). Depending on the width of the cut, the depth and rake angles of most tillage tools; soil-tool interactions affected failure patterns, area of soil cut and soil throws, furrow depth, ridge distance, and height (Manuwa and Ogunlami, 2010). For instance, all rake angles of 15, 30, and 45° caused brittle failure profile patterns at various tillage depths (3, 5, and 7cm), bending failure patterns at only 30° and 45° rake angles (and both 5 and 7cm depths) and chip-forming failure profile at only at 15° and 3cm tool depth (Tagar et al., 2016). Researchers have studied soil-tool interaction parameters and soil mechanical behavior, constitutive failure mechanisms, their resultant effects, and the final deformed states as shown in Figure 3. However, parameters that ought to define the deformative behavior of soil-tool interactions and the desired failure and quality of soil working, are enormously diverse and have not been unanimously quantified and documented.

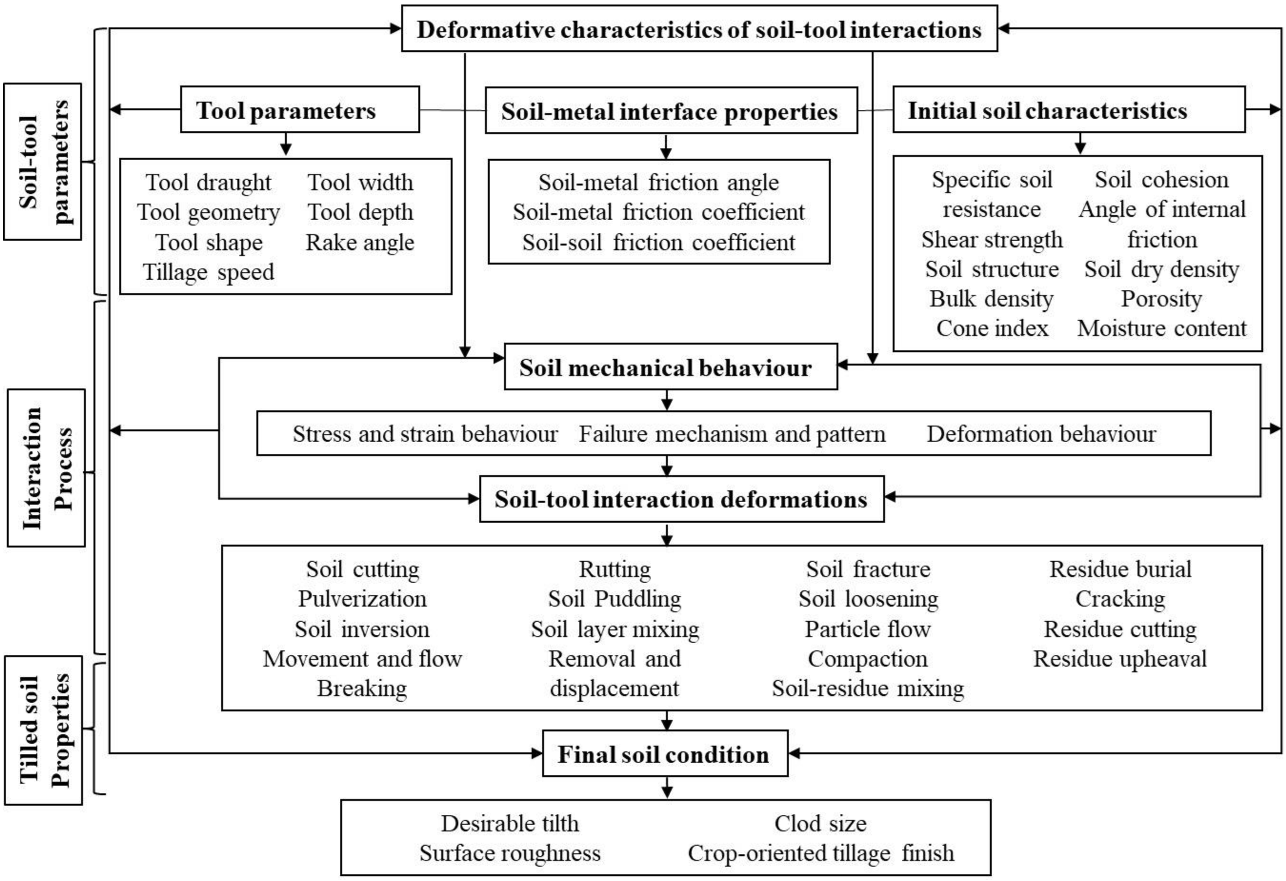

Figure 3 Deformation characteristics of soil-tool interactions in tillage

2.1.2 Mechanical pulverization of arable soils

Mechanical pulverization of arable soils fractures the soil structure and segregates soil clods into variable-sized soil aggregates due to multivariate and heterogeneous soil states in situ (Barr et al., 2018). The intensity and effects of mechanical pulverization varied with soil bulk density, cone index, porosity, moisture content, cohesion, and shear strength (Ordoñez-Morales et al., 2019). Pulverization of cohesionless sandy soils caused an easy soil failure compared to cohesive and adhesive clays (Hoseinian et al., 2022b). According to Conte et al. (2011), loam soils were more prone to undesired tool-induced fragmentation compared to clays. In contrast, mechanical pulverization of clays produced a more uniform tilth than loams and clay loams while oxisols produced a higher disturbance index than alfisols (Conceição et al., 2016). However, desirable seedbed tilth was more uniformly achieved by pulverizing moist soil than dry soils (Aikins et al., 2020). Soil-tool interactions in wet clays led to the hair-pinning of soil and weeds on the tooling components as moist clays stuck onto furrow openers (Baker et al., 2007). Dry and friable soils improved pulverization ratios by 47.76% compared to both moist soils, and moderately moist soils (16.47%), while the highest pulverization ratios (74%) were achieved at low soil penetration resistance (623.47 kN m^{-2}), low bulk density (0.96 g cm^{-3}) and high porosity (63.90%) (Nassir, 2018). However, dry soils caused excessive and undesirable crumbling, increased tool wear, and demanded excessive tool draft and soil deformation forces at the soil-tool interface (Balsari et al., 2021).

Apart from soil properties, pulverization effects were dynamically influenced by the relative interaction of respective soil-tooling geometries and their dynamically variable forces, shear angles, and tool speed at various depths (Zeng et al., 2017; Bulgakov et al., 2019). For instance, increasing pulverization ratios of disk harrows, chiseling, and moldboard plows by 5.30, 28.66, and 43.61% reduced the mean clod weight diameters of resultant tilth by 16.77, 18.47 and 26.01% respectively (Khadr, 2008). Mechanical pulverization by subsoiler tools improved soil bulk density and crust strength of sandy loams by 7% and 15% respectively. On the other soil pulverization with tied ridge tools improved the soil water holding capacity of resultant tilth by 16% and 17% compared to ox plows and subsoilers respectively (Miriti, 2013). In contrast, the pulverization action of moldboards and disk tool geometries caused soil crusting and plow pan in hard-setting soils (Gitau et al., 2006). Pulverization action at the soil-subsoiler and soil-ripper interface loosened and fissured compacting soils and reduced soil-root penetration impedance (Mwiti et al., 2022; Gitau et al., 2008). Compared to chiseling, moldboard plows increased the soil pulverization index by 32.57% in silty loams (Nassir, 2017). According to Muhsin (2017), a high pulverization ratio (51.72%) and pulverized soil volume (85.10%) were achieved while chiseling at 20 cm depth at high tillage speed (4.9kph) while 30 cm tool depth reduced pulverization ratio (45.83%) but increased plowed soil volume (87.38%). Thus, soil properties and tool-implement geometries ought to be considered against anticipated tool working parameters and desired level of soil fragmentation and tillage finish in optimizing tool design (Schjønning et al., 2015; Zhu et al., 2017; De Pue et al., 2020).

3 Constitutive effects of tool parameters on soil-tool interactions

Soil-tool interactions, deformation and failure mechanisms, and the resultant tilth profile vary with tillage tool parameters (Nunes et al., 2020). The effects of tool parameters on tillage-force-deformation behavior are dynamically and relatively multivariate because tool-implement forces and stresses are multi-dimensionally transmitted to variably pulverize the soil en masse (Keller et al., 2013). Moreover, soil disturbance and failure front profile depended on the intensity of tool-implement forces and the number of soil manipulations that are all influenced by tool geometry, tool speed and depth, rake angles, and tool-implement configurations (Alzoubi et al., 2020).

3.1 Tillage tool geometries and soil-tool interactions

Tillage tools break down the original soil structure as particles shear and move around and ahead of the dynamically propagated failure front (Karmakar and Kushwaha, 2005). The geometric configuration of tillage tools influences the intensity and the manner of soil-tool interaction, soil-residue mixing, operational energy requirements, soil cutting forces, and tillage performance index (TPI) and quality (Arvidsson and Hillerström, 2010). The need for tool-implement adjustments such as tine-foot width, lift height, and critical depth to achieve the desired degree of soil disturbance and loosening for a range of heterogeneous soil and field conditions requires accurate pre-evaluation of various soil-tooling geometries.

3.1.1 Effect of the straight shank and curved tines tool geometries

The geometric parameters of the straight shank and curved tines influenced the degree of soil disturbance, failure front patterns, surface ruggedness, draft forces, soil reaction forces, shape and size of soil clods, soil upheaval, and the resultant tilth (Horn et al., 2019). Narrow shank tines improved the working depth uniformities beyond 70%, with less than 5% soil disturbance and overturn rates (He et al., 2021). Soil overturn rates, disturbance and bulkiness coefficients for very narrow tillage tines ranged between 0.5%-14.5%, 50%-68%, and 12%-40%, although the 14 mm thick tines produced the most desirable performance at 45° rake angle and 60° and cutting-edge angles respectively (Sang et al., 2022). Wide tool blade tine geometries caused more upward and forward soil failure while loosening the soil in a crescent manner (Dula and Anawute, 2021). Three-dimensional soil loosening and failure from winged chisel tine geometries produced more soil disturbance and pulverized areas compared to two-dimensional dual-bent blade geometries (Salar et al., 2013). Compared to rectangular flat tools, soil disturbance, and displacement at the lowest draft, pulverization forces, and tillage energy were better achieved by trapezoidal tine geometries (Elbashir et al., 2013). Apart from inducing the highest vertical soil displacement and better soil disturbance, trapezoidal soil-cutting tools reduced tillage draft forces by 29.8%, 29.7%, and 18.5% for all tool rake angles (90°, 60°, and 30°) compared to rectangular flat tool geometries (Ahmed et al., 2014). The largest to smallest soil penetration resistances were respectively produced by rectangular, crescent, triangular, and trapezoidal tine geometries (He et al., 2016). Trapezoidal tooling geometry reduced soil-tool contact surface area and optimized soil cutting at reduced draft forces (Ahmed et al., 2014). Wing-shaped tool geometries increased the total soil disturbance area by 50% at useful working depth and improved the effectiveness of soil loosening with smooth surfaces, although draft requirements increased by 30% (Dula and Anawute, 2021).

Tine opener configurations performed better in minimizing undesirable pulverization and soil disturbances compared to disc-type furrow opener geometries (Mari et al., 2015). Although dual-bent blades produced higher disturbed areas compared to winged chisel tines, clod mean weight and diameter from winged chisel geometries were significantly higher (Salar et al., 2013). In contrast dual bent-blade tool geometries significantly improved surface residue retention at low draft requirements than winged chisel geometries (Askari et al., 2017). According to Manuwa and Ogunlami (2010), soil-tool interactions of semicircular concave tools utilized the least specific draft compared to the semicircular flat blade and rectangular tool blade geometries. Curved tillage tool geometries utilized 7% to 20% less draft than straight tine and shanks for effecting equal soil breakup and failure in compacted cohesive soils (Kumar and Sharma, 2020). Concave tine furrow openers had the maximum straw disturbance (20.7%) compared to compared to convex, linear, and combined tillage tine types that reduced straw disturbance by 29.3% , 16.3% and 10.6% respectively (Zhang et al., 2016). Researchers opined that soil tooling geometries be embodied with qualities of leaving crop residues on the soil surface, non-inversion disturbance of the upper arable layer, and non-compaction-related disruption of soil structure (Bravo et al., 2014; Mwiti et al., 2023). A developed dual-bent blade tool geometry with a rake and bend angles of 7.5° and 10° respectively retained a significant amount of surface residue compared to winged chisel tines (Salar et al., 2013). Inward chamfered tine blade shares completely pulverized the soil (74%) to a fine tilth with only a maximum of 26% loose soil falling out of the worked furrow compared to counterproductive strains of the outward chamfered cutting edges (Matin et al., 2016). As such the tool geometries ought to be designed in a manner that promotes cutting with desirable particle fragmentation, low residue-blade entanglement, reduced tool strain, and tillage energy consumption (Chertkiattipol and Niyamapa, 2010).

3.1.2 Influence of rotary and disc type geometries on soil tool interactions

Rotary and disc geometries have gained popularity in the design of tillage tools due to reduced traverse, improved operational timeliness, and seedbed quality in a one tillage finish (Hensh et al., 2021a; Vegad et al., 2017). Soil tool interactions with rotary tillage tools have produced beneficial tillage results such as improved disturbance and increased residue incorporation quality, desired burial rate, and distribution uniformity (Xu et al., 2022a). For instance, rotary and spiral blade tools improved soil disturbance intensity by 25% and 30% respectively with a 20% increase (from 15 to 18cm) in tillage depth (Du et al., 2022). However, the effects were variably dependent on geometric configurations such as the number of rotors, rotor radius, and arrangement and velocity ratios (Raparelli et al., 2019; Matin et al., 2016). The rotation speed of rotary tools had the greatest influence on soil fragmentation intensity, soil throw characteristics, and furrow backfill (Yang et al., 2023). Compared to moldboard plowing, reverse-rotational rotary tillers increased the tillage quality index by 13.1% and improved soil homogenization within 20 cm tillage depth (Zhang et al., 2018).

Pulverization uniformity, alleviation of excessive trash, residue, and straw incorporation efficiencies, and distribution uniformity were better achieved by active rotary tools compared to passive rotary type (Xu, Xie and Matin et al., 2022). For instance, residue incorporation and straw burial rates of 95.5% were achieved at a rotary speed of 320 revolutions per minute (rpm) at 13 cm tillage depth with relative errors of less than 5% by an optimized 250 mm-diameter rotary tool (Xu, Xie and Matin et al., 2022). Rotary offset disc harrows produced high tillage performance indices (maximum soil pulverization and residue burial efficiency) at a minimal fuel energy consumption of 8.81 and 14.56 for velocity ratios (implement axle per tractor forward speed) of 4.59 and 4.06 during the first and second passes respectively (Upadhyay and Raheman, 2020). However, the highest soil throws were achieved by semicircular flat blade geometries followed by semicircular concave tools and rectangular tool blade geometries respectively (Manuwa and Ogunlami, 2010). In contrast, rotary bent blades achieved the best soil fragmentation and highest soil throws (70%) and high furrow backfill rates (60%) compared to the backfill rate of hole blade rotary tools (36%) and only 8% backfill rates of straight rotary blades (Yang et al., 2023). However, soil interactions with furrow disc opener geometries disrupted the furrow profiles and reduced the desired quality of surface tilth and tillage finish compared to tillage tines (Baker et al., 2007). Moreover, disc furrow openers caused less soil disturbance due to poor penetration compared to tine geometries, which had a good penetration depth, though they concurrently demanded high tillage draft (Aikins et al., 2020).

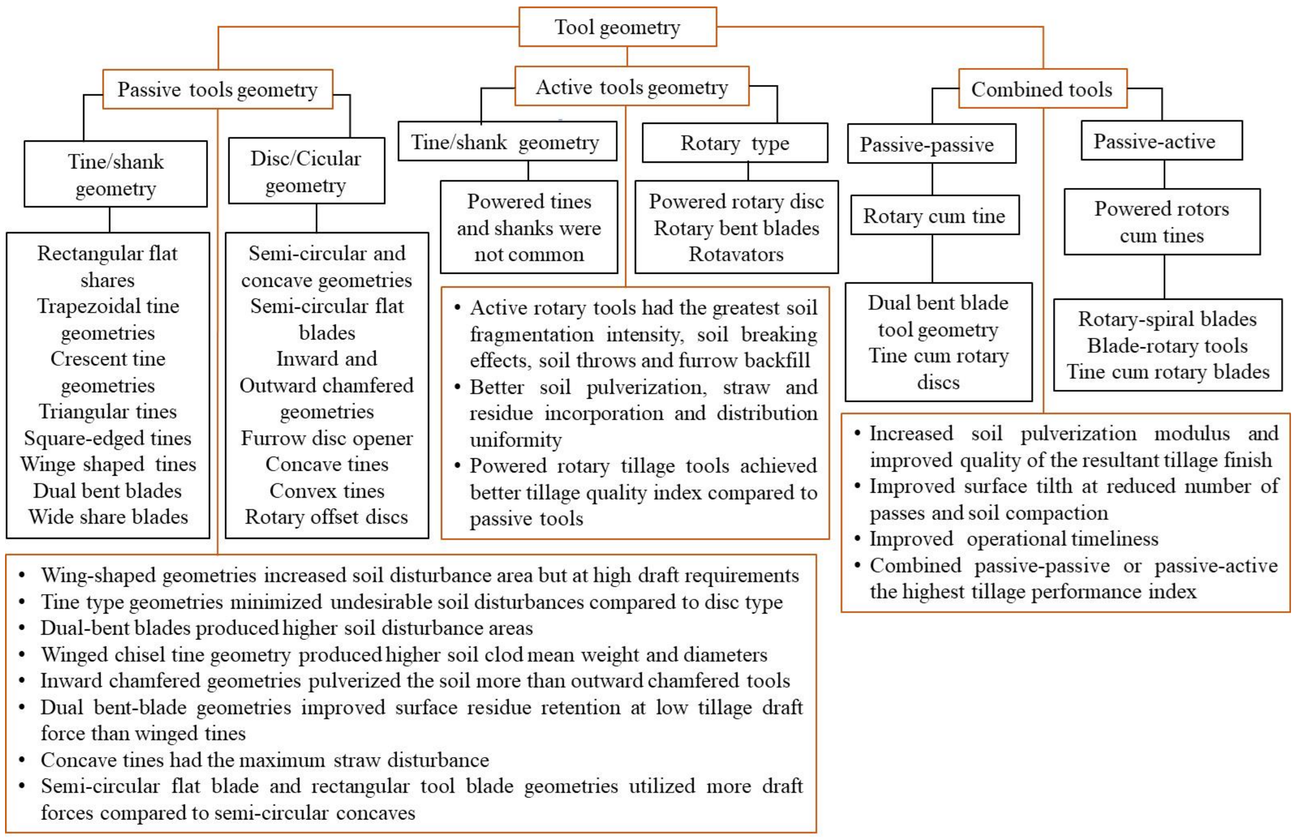

Figure 4 Soil-tool interactions and mechanical pulverization of various tool geometries

3.1.3 Soil-tool interactions of combined tillage tool configurations

Soil-tool interactions of combined tillage tool configurations utilize two or more geometries of soil working elements to accomplish soil pulverization and disturbance. Combined cultivator cum single-acting disk harrow, combined rotary-chisel tine, and combined shank-bladed disks increased soil pulverization modulus, reduced soil clods, and improved tillage uniformity and aeration and moisture holding capacity of the resultant tillage finish (Prem et al., 2016). A combined subsoiler-rotary harrow pulverized soils by reducing their mean clod diameters by 13.7% (from 22.98 to 19.83mm) and 16.4% (from 31.77 to 26.57mm) for clay and clay loams respectively (Usaborisut and Prasertkan, 2019). Apart from achieving the desired tilth and tillage performance at a reduced number of passes, the combined rotavator cum cultivator tool reduced soil compaction by 27% compared to rotors alone (Behera et al., 2021). The configuration of a rotary hoe combined with a farrow opener increased soil fragmentation by 10% and reduced fuel consumption by 16% compared to conventional furrow openers (Barbosa, 2020). A similar trend was observed while using rotary tiller cum disc harrow, disk plow cum rotary blade, and spiked clod crusher cum spring tine cultivator than individual tools (Prem et al., 2016). Soil pulverization with combined furrow opener tines increased the bulk density of loams and sandy loams by 3.6% and by 3.5% respectively compared to 2.7% and 0.9% respectively while using either single-acting concave and linear type or convex type tillage tines (Zhang et al., 2016).

Depending on the tool geometry, increasing the depth and speed of the advancing tool affected soil disturbance intensity, straw incorporation, and residue burial rate of various active, passive, and combined implements (Mari et al., 2015). Moreover, the soil bite size by the geometrical orientation of the tool affected the size of resultant pulverized soil clods, clod chip dimensions, and the resultant tilth profile and surface roughness (Usaborisut and Prasertkan, 2019). The effect of soil-tool interactions and mechanical pulverization of various tillage tool geometries compare as shown in Figure 4.

3.3 Influence of tillage depth on soil-tool deformations

Tillage depth influenced furrow areas, ridge heights, and the intensity of forward, lateral throws, and rearward soil throw. According to Marakoğlu et al. (2021), increased tillage depth caused a more significant increase in a disturbed area of soil but at a higher draft force compared to increased tillage speed. Increasing the tillage depth of chisel tines by 75% caused a 53% increase in soil disturbance area with a 49% increase in draft force. For instance, a three-fold increase in the tillage depth of rotavators (from 5 cm to 15cm) increased soil disturbance but increased rotavator torque requirements by 59.46% (Hensh et al., 2021b). According to Spoor and Godwin (1978), there exists a critical tillage depth beyond which soil-tool interactions produced undesirable soil loosening, compaction ensued and specific soil resistance and tillage energy increased. However, such critical depths were dependent on the width, inclination angle, and lift height of the tool (Aday and Ramadhan., 2019; Ndawii et al., 2011). For instance, the critical tillage depth of subsoilers for optimal soil loosening at low tillage energy consumption was established at 380 mm (Song et al., 2022). High soil disturbance, residue incorporation, and straw burial rate (95.5%) were significantly influenced by varying the depth of tillage compared to the tool speed (Xu et al., 2022b). Moreover, tillage depth had the greatest effect on the draft energy consumption followed by tool width and speed respectively (Moeinfar et al., 2014). For instance, increasing tillage tool share width by 100% and speed by 114% resulted in an 80% and only 17% increase in soil disturbance area respectively (Marakoğlu et al., 2021). Nonetheless, compared to tool geometry, tillage depth had the least influence on the degree of soil disturbance, soil segregation, and pulverization force response characteristics but the highest influence on tillage draft.

3.4 Influence of tillage tool speed on soil-tool interactions and failure

The speed of tillage tools influenced the shearing rate, soil flows, and profile of the advancing soil failure front. Although cohesion and angle of internal friction influenced soil shear resistance, the shearing rate of arable soils was more significantly influenced by the tool speed (Gitau et al., 2006). Moreover, side crescent soil failure rate and horizontal and vertical force reactions of soil increased with tillage speed (Godwin, 2007). Higher tillage speeds increased disturbed furrow heights and volume of displaced soil with an increase in tillage depth for tines, sweep, and shovel tools (Bögel et al., 2016). Soil disturbance area increased by 67% (from 0.18 to 0.3 m^2) by increasing the tillage speed of a single pass disc tool by 98% (from 1.25 to 2.47 m s^{-1}) at a three-fold increase (from 5 to 15 cm) in tool depth (Chandio et al., 2020). The influence of tool speed on soil tool interaction and soil failure is relatively constrained by failure-dependent components of the tool geometrical configuration and the conditions of respective soil types (Kumar and Sharma, 2020). Doubling the tool rotor speed and the forward tillage speed of rotary tools decreased the mean clod diameter of the resultant tilth by about 0.4 cm at a tillage depth of 0-20 cm (Usaborisut and Prasertkan, 2019). Researchers reported soil failure front and failure depth of 16 cm and 10 mm respectively operating at 6 m s^{-1} tool speed and 10 cm tillage depth and established 5 to 6.5 m s^{-1} as the critical soil failure speed range (Karmakar and Kushwaha., 2005). Increasing tillage speed significantly increased the draught of tillage tools and the relationship varied from linear to quadratic (Odey et al., 2018; Godwin, 2007). However, compared to tillage depth, tool speed had a lesser influence on increased draft forces of tillage tools under similar soil conditions (Moeinfar et al., 2014; Al-Suhaibani, 2010). Further studies are required to parametrize the effects of tillage speed with soil-residue interaction and tillage finish.

4 Soil-tool interaction and tillage quality

The effects of soil-tool interactions on tillage quality have been reported using various indicators, parameters, and performance levels. Tillage tool designers have often focused on the minimum draft, low tractor power, and low tillage energy requirements at maximum soil fragmentation to parametrize tillage performance (Berntsen, 2002). However, tillage tool users were much more concerned with the characteristics of the resultant tilled soil and crop-oriented quality of the tillage finish as the most appropriate parameters for describing tillage quality (Bögel et al., 2016; Zeng et al., 2017). As such, different studies have associated various soil-engaging tools with various performance parameters and tillage quality indicators (Chen et al., 2013).

4.1 Soil-tool interactions and quality indicators of the resultant tilled soil

Researchers explored the resultant effect of soil-tool interactions based on desirable soil working quality, evaluated using surface tilth and soil-failure profile patterns (Karuma et al., 2014). The percentage of soil fragmentation and loosened areas have been parameterized for measuring and evaluating the performance of soil-tool interactions and tillage quality (Jin et al., 2021). Further, the cross-section area of disturbed soil, soil failure front profile, failure propagation pattern, and draft per unit area of disturbed soil was also used to assess the quality of desired soil-tool interactions (Zeng, 2019). The surface roughness coefficient, the proportion of disturbed surfaces and the quality of desired tillage finish need to be considered while defining the quality of soil tillage (Riegler-Nurscher et al., 2020). Less dislodged soil, greater porosity change, and low working draft parametrized tillage performance of subsoilers (Li et al., 2016). Soil-tool-residue-cutting, residue incorporation, mixing and burial, soil-residue movement and displacement forces, clod size reduction, and pulverization intensity ought to be adopted in qualifying overall tillage performance (Zeng and Chen, 2019). Moreover, tool width, resultant furrow depth, the maximum width of soil cut (crescent) and throw, ridge height and ridge-to-ridge distance were used to define tillage performance (Manuwa, 2009). Soil-residue gashing and mixing intensity, surface residue retention, degree of soil overturn and the magnitude of pulverizing forces parametrized tillage performance in conservation tillage (He et al., 2016; Harrigan et al., 2006).

Some of the researchers considered drought power input and energy consumption as the most important measure of qualifying soil-tool interaction and tillage performance (Marey et al., 2020; Bashir et al., 2015). As such, characterizing either tillage draft and energy consumption or soil-tool disturbance, mechanical pulverization, and deformation of arable soils for defining tillage performance has not achieved consensus. Nonetheless, improvement in the quality of work regarding the physical-mechanical properties of the tilled soil would be desired whenever it was associated with a reduction in draft forces, energy requirements, and improved penetration of tillage tools (Varani and Mattetti, 2023). Some of the reviewed effects of soil-tool interactions and parameters under various investigations in tillage are summarized in Table 1.

Table 1 Effects of soil-tool interactions in tillage

Parameter(s)	Investigation(s)	Effects of soil-tool Interaction(s)	Reference(s)
Surface roughness	Effect of soil-tool interactions on soil surface roughness, infiltration water ponding, and runoff in tilled soils.	Rough surfaces had high Infiltration of water and greater than that on the smooth surfaces for the different rainfall intensities.	Zhao et al., 2018 (Shaanxi, China)
	Soil roughness visual detection in tillage.	A high correlation between soil roughness and tillage intensity as well as homogenizing effects on soil roughness was observed.	Riegler-Nurscher, et al., 2020 (Austria)
Aggregate stability Bulk density Penetration resistance	Effects of soil-tool interaction intensity on structural indicators of soils in the US.	Reduction of moldboard pulverization intensity to No-till improved aggregate stability and slightly decreased bulk density and Penetration resistance.	Nunes et al., 2020 (U.S.A)
a) Rake angles	Effects of rake angles on soil translocation, throw, and movements.	Low opener rake angles moved deep tracers and threw deeper soils more than large angles. Large angles disturbed small furrow sizes but achieved more backfills.	Solhjou et al., 2012 (Austria)
Soil displacement Geometry of soil-tooling	Modeling approach for dynamic soil displacement response, due to soil interaction with sweep cultivation tools.	The geometry of the soil-tool active interface accounts for soil. displacement by the tooling impact in terms of particle size distribution and their potential contact density on the active tool surface.	Milkevych et al., (2018) (Denmark)
Opener geometry Soil type Tillage depth Tine opener tip angle	Analysis of three hoe-type furrow openers on working depths, disturbed soil, tine tip angles, and performance of tractors in Brazil.	Opener geometry and soil type affected soil disturbance and machine performance directly. From the evaluated depths (6.0, 9.5,10.5,12.0, and 13.5 cm), soil disturbances were highest at working depths of 10.5,12.0, and 13.5cm. Compared to 27 °, and 17 °, the highest tine opener tip angle (29 °) had the highest fuel consumption per unit volume of disturbed soil but lower tractive demand and fuel consumption at a depth of 13.5cm. Working at greater depth, a rake angle of 27 ° optimized soil disturbance with fuel consumption without reducing productivity.	Bertonha et al., 2015 (Brazil)
Tine opener types Tool geometry Tool settings Tine interactions with soil	Soil-tool interactions and performance of tine openers.	Compared to disc openers tine openers cause higher soil disturbances even though disking causes residue hair pinning. Wing-tined openers reduced residue interference with seeding and supported higher lateral soil spread. Inverted-T openers achieved subsurface soil shattering, moisture conservation, and better seed-soil contact. Concave-edged tine openers reduced soil perturbation compared to convex-cut-edged openers. Increased rake angles, tine widths, and operating depths increased soil disturbance and draught requirements. Low draught and penetration forces of bent-leg opener were associated with minimal lateral throws, but high furrow backfills.	Aikins et al., 2020 (Australia)
Forward speed Tool depth Blade width, Draft force	Soil-tool interactions under different working tool parameters on cultivar performance and soil disturbance.	Soil disturbance was significantly increased with increased speed, working depth, blade width, and draft forces. The highest mean disturbed worked area was obtained from the profiles with dry conditions at the highest working speed and vice versa.	Abbaspour-Gilandeh, et al., 2020 (Iran)
Soil throw Rake angles Soil-tool impact Surface soil cover	Effects of rake angles on narrow opener performance.	Increased rake angles reduced the mass of upheaved soils. The characteristic disturbances between the opener action of high and low rakes upheaved soils with particle dispersion. The direct impact of soils with tillage shanks increased with rake angles. Increased rake angles and associated direct soil-tool impacts enhanced breakage of cohesive particle bonds and increased individual particle throws.	Barr et al., 2018 (Australia)

Parameter(s)	Investigation(s)	Effects of soil-tool Interaction(s)	Reference(s)
Number of tines (single and multiple) Types of tines foot bulk density and moisture content	Review of implementing geometric effects and forces on soil failure.	The percentage of loose particles on the surface increased with decreased rake angles. Single tines disturb the soil in an upward and forward failure pattern tending to loosen the soil in a crescent manner. Multiple tines increased draught forces, and disturbed areas but lowered specific soil resistances. Attaching wings or sweeps to tines modified soil disturbance by doubling the disturbed areas and increasing tillage draughts by 30%. Wings and sweeps significantly increased tillage effectiveness by lowering specific resistance, draught, and disturbed areas by 30%. Dry and more dense soil disturbance produced crescent failures at greater depths than wet loose soils for a given implement shape.	Godwin, 2007 (Silsoe, UK)
Tillage speed Cutting forces Residue burial Kinetic energy Draft forces	Soil-tool-residue interaction modeling and the influence of working speed on tillage performance of four chiseling tools (narrow sweep, wide sweep, reversible shovel, and twisted shovel).	Tillage speed was congruent with soil displacement, cutting forces, residue displacements, and cover reduction with kinetic energy. Increased tillage speed decreased contact numbers between soil and residue of chiseling tools. Compared to sweeping tools, shovel chiseling tools had higher soil and residue disturbance and burial with lower drafts forces. The twisted shovel geometry had the most effective residue incorporation, the highest soil contacts, and the least vertical force while the reversible shovel had the least draft force for all tillage speeds.	Zeng et al., 2020 (Manitoba, Canada)

4.2 Tillage quality and performance of passive, active, and combined tillage tools

While active tillage tools utilize tractor power take-off, passive tool implements are only trailed by the drawbar. Compared to passive tools, active rotary tools increased soil pulverization and improved soil-residue interaction, overall tillage quality, and performance (Du et al., 2021; Sarkar et al., 2021). Optimizing tillage energy and soil-tool interactions with operational timeliness necessitates the establishment of combined active-passive or passive-passive tillage tools for one tillage finish. For instance, subsoiler-rotary harrow combination reduced overall tillage power requirements by about 5% (from 15.3% to 10.5%) compared to same tillage tools working separately (Usaborisut and Prasertkan, 2019).

Combined tillage tools improved mechanical loosening and enhanced finer pulverization modulus, surface uniformity, and random roughness index of tilled soils at reduced traverse (Kailappan et al., 2001). Combining mouldboard tools with ripper shanks reduced soil clod sizes and diameters, and improved the surface roughness index indicating superior tillage performance compared to the individual tools (Sarkar et al., 2021). High TPI (0.94) corresponding to the highest time (61.1%) and fuel (49.8%) savings per hectare at the lowest tillage energy demand (681.36 MJ ha^{-1}) was achieved by combined offset disc harrows while the highest TPI (1.26) and high energy (1105.86 MJ ha^{-1}) at lowest fuel (17.9%) and time (40.6%) savings for double type rotavators alone; compared to 0.54 and 1360.4 MJ ha^{-1} lowest TPI and highest energy demand respectively for purely passive cultivator-disc harrow combination(Choudhary et al., 2021). Soil-tool interactions of combined active tillage tools were energy and fuel-efficient by up to 34% compared to passive tool configurations (Sarkar et al., 2021). Combined active-passive tillage tools comprising of subsoiler-rotary harrow combination reduced the overall subsoiling draft by 4.4%-11.3% compared to individual subsoilers (Usaborisut and Prasertkan, 2018).

Reduction of clod sizes by 60.73% was regarded as the optimal tillage performance of powered disc harrows in sandy clay loams, although it was associated with increased fuel consumption by 18.4% compared to passive rolling harrows (Upadhyay and Raheman, 2019). However, combining four passive tool elements with active tillage tools reduced fuel consumption by 20% compared to the operation of the active tools alone (Manian and Kathirvel, 2001; Sarkar et al., 2021). Combined offset disc harrows and double rotor type rotavators produced a more desirable soil fragmentation and TPI (133.33%) compared to single rotor type (88.88%) configurations (Choudhary et al., 2021). Triple combined tillage implements comprising of a four share-mouldboard plow, rigid harrow tines, and the leveling board achieved the desired soil clod diameter, improved the roughness index and soil bulk density, but was associated with 9% increase in wheel slip (from 8% to 17%) compared to individual moldboard plows (Alkhafaji et al., 2018). Combined tillage tools saved as high as 55% of seedbed preparation time and tillage operational costs by up to 44%-55% (Kailappan et al., 2001). For instance, combined offset disk harrows had better time savings (61.1%) compared to double rotor (40.6%) and single rotor type rotavators (9.54%) in achieving the same quality of tillage (Choudhary et al., 2021).

From the foregoing, soil-tool interactions are fundamental to the tool design, considering their critical role in optimizing tillage quality and performance. However, collecting accurate design data on the mechanistic behavior of soil-engaged interface at depth amid soil heterogeneity in situ is tedious and time-consuming (Zeng et al., 2017). Performance experimentation for each of the reviewed tool parameters and operational settings under numerous soil conditions for which the tool could be investigated is cumbersome and resource-intensive (Tekeste et al., 2019). Thus, computational assistance has been explored to study and evaluate the numerous effects of soil-tool interactions.

5 Computer-aided modeling and simulation of soil-tool interactions

Researchers have explored computational assistance to demystify multi-parametric complexity and dynamic interactions of tillage tools with heterogeneous properties of arable soils (Edwards et al., 2016). Computational models have been evolved for the simulation and prediction of complex deformation non-linearities of soil-tool interactions, dynamic failure mechanisms, tool-force reaction behavior, and their effect under various operating conditions (Schramm et al., 2020; Robbins et al., 2021; Hoseinian et al., 2022a). Zeng et al.(2020) developed a discrete element model (DEM) of the soil-tool interactions that predicted soil tool cutting and disturbance of a soil-subsoiler with a low range (2.63% to 10.2%) of relative errors. Renon et al. (2005) successfully simulated single tine plowing using 3D models of the finite element method (FEM) and large deformation software, Forge3®, and optimized the plowing process by improved soil-tool interactions. Validated DEM models predicted soil disturbance parameters such as furrow cross-sectional area, width, and critical depth with a low range (1% to 19%) of relative error (Aikins et al., 2021). Researchers analyzed the dynamic behavior of soil-rotary tool blade interaction and successfully simulated macro and meso-movement of soil particles using DEM with an average soil-side displacement error of 15.3% (Fang et al., 2016). Tillage modeling in FEM and the large deformation software package (Forge3®) showed their successful coding capability in examining rake angles, critical forces, and complex soil flow patterns (Renon et al., 2005). A 3D finite element analysis (FEA) of a toothed disk showed a reduction of tool stresses and tillage forces by 22.8% with improved straw incorporation efficiency of 26.3% (Torotwa et al., 2022). Compared to field results, prediction of soil displacement, and horizontal and vertical forces of moldboard was successfully achieved using DEM with average relative errors of 1.3%, 3%, and 4.4% respectively whilst vertical forces were more accurately regressed (coefficient of determination, R^2=0.99) than horizontal forces (R^2=0.98) components (Makange et al., 2020). According to Drwish (2020), the Visual Basic software environment simulated soil-tool interaction parameters of simple tillage tools and validated the prediction model with accuracy levels of 95%, 86%, and 85% for tool depth, rake angles, and tool speed respectively.

The complex effects of soil-tool interactions have been studied using artificial neural network (ANN) models (Al-Janobi et al., 2020). Saleh and Ayman (2013), considered soil conditions as input parameters of ANN models and tillage performance (forces and degree of soil pulverization) as the prediction output and the models correlated well with experimental data (low relative error, ±2%). ANN achieved the highest correlation coefficient (R^2) of 0.9445 and simulation accuracy of 99.83% in predicting draft forces of a chisel plow under variable soil properties compared to 0.592 and 61% respectively from linear regression models (Abbaspour-Gilandeh et al., 2020). However computational capability of the adaptive neuro-fuzzy inference system (ANFIS) provided better accuracy, low mean square error (MSE), and high R^2 (0.0156 and 0.998 respectively) compared to other methods (Askari and Abbaspour-Gilandeh, 2019).

Computational simulations and modeling of soil-tool interactions provide opportunities for the functional design of tillage tools at reduced field testing and verification time, although some models attracted significantly high computing costs (Milkevych et al., 2018; Zeng et al., 2020; Ani et al., 2018; and Tekeste et al., 2019). Moreover, some of the models were subject to multi-collinearity problems and were limited to the soil conditions under which they were developed. Simplified field-scale models for characterizing the dynamic behavior of soil-tool interactions and tillage energy with desirable tillage finish have not been furnished.

6 Conclusion

Parameters that characterize the effects of soil-tool interactions, pulverization, and tillage performance and quality have not been unanimously defined and adopted. Parameters such as soil disturbance index, residue retention, soil-residue mixing, surface tilth uniformity and roughness coefficient sparsely integrated the effects of soil-tool interactions with tillage forces and energy requirements. Although tool geometry had the greatest influence on soil pulverization and failure, tillage depth had the greatest influence on increased draft force requirements compared to tillage speed. However sufficient pulverization at minimal energy consumption was achieved at low rake angles, average speed, and sufficient tillage depth for most soil tooling geometries. Semi-circular and concave tool geometries utilize low tillage drafts compared to flat and rectangular blade geometries. Desirable soil pulverization is achieved by trapezoidal tool geometries but at a lower overall tillage performance index compared to rotary tools.

The effect of soil-tool interaction and properties of the resultant tillage finish can sufficiently define tillage performance if associated with reduced draft forces, fuel consumption, tillage cost, and improved operational timeliness. Further research is required to furnish allowable levels of pulverization intensity and draft utilization limits that would not significantly compromise desirable tillage finish to avert tillage-induced soil degradation. Such limits could be published in available standards such as ASABE standards to guide tillage tool designers and users. In-depth studies on stress-strain relations at the soil-tool interface can be explored for constituting integrated field-scale models for the evaluation of overall tillage performance. This review forms a reference for guiding the designers and users of new soil working elements in instrumenting and optimizing soil-tool interactions, tillage finish, and overall tillage performance.

Declaration of competing interest

The authors have no conflicting interests in this review.

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