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Impact of agronomic practices on physical surface crusts and some soil technical attributes of two winter wheat fields in southern Iraq

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Abstract

Purpose Agricultural management as tillage systems and manure application can contribute effectively to controlling physical surface crusts (SCs), improving the soil's technical characteristics and germination rates. While agronomic practices are generally applied to winter wheat fields in southern Iraq, no previous study has explored their impact in combination with SCs and soil physical attributes on wheat productivity (WP) under different soil textures.

Materials and methods The impact of different agronomic management practices on the formation of soil physical surface crusts (*SCs*), soil compaction (measured by soil penetration resistance, *SPR*), soil volumetric water content (*VWC*), soil bulk density (ρb), mean weight diameter of aggregates (*MWD*), and WP was examined in two soil textures (clay loam, clay) during 2020 and 2022.

Experimental data were subjected to an identical and randomized complete block design (RCBD) under a nested-factorial experimental design, where nine treatments with three replicates each were selected. This included three tillage practices (conventional tillage system (CT), till-plant (TP), and rotational tillage (NTCT)), alongside a sub-treatment with organic fertilizers (cattle manure (CF), and wheat straw (WR)), or without added fertilizer (WT).

Results and discussion Results showed that CT treatment increased SCs during wheat growth stages by significantly increasing aggregate stability. A significant difference in ρb and *SPR* and a higher distribution of *VWC* were seen under CT treatment when compared to TP and NTCT treatments. TP treatment showed a significantly increased in *SPR* and ρb, particularly in clay loam. The *MWD* under TP and NTCT was significantly different to CT treatment, which may be explained by an increase in soil stability due to their management practices. Additionally, both organic fertilizers (CF and WR) significantly enhanced *SCs*, *SPR*, *VWC*, ρb, *MWD*, and *WP*.

Conclusions These data showed a strong relationship between *SCs* and ρb and between *VWC* and *SPR*, which are directly affected by the soil's water content.

Keywords Tillage practices · Organic fertilizers · Soil productivity · Agronomic management · Semi-arid climate

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1 Introduction

Soil mechanization for the preparation of cultivation is considered one of the most important and complex soil management practices (SMP). The adoption of SMP that does not involve turning over soil layers is notably important for the maintenance of soil aggregates stability (Fernandes et al. 2023). SMP, such as tillage and fertilizer applications (FA), have been shown to progressively aid soil stability in combination with the effects of rainfall, particle resettlement, and cycles of wetting and drying (Al-Shammary et al. 2020; Sarker et al. 2018).

Choosing an appropriate SMP is crucial to control the quality of tillage and preserve the soil's physical properties, including soil bulk density (ρb) (Yuan et al. 2022), soil penetration resistance (*SPR*) (He et al. 2019; Souza et al. 2021), soil organic carbon (*SOM*) (Gao et al. 2017; Oliveira et al. 2022), soil water storage (*SWS*) (de Oliveira et al. 2019; Zhao et al. 2022), soil structure (Obour et al. 2017), soil texture (Sarker et al. 2018; Xiang et al. 2022), mean weight diameter of aggregates (*MWD*) (Wang et al. 2019), and surface crust (*SC*) formation (Chamizo et al. 2015; Gicheru et al. 2004).

Conventional tillage (CT) turns over the soil's surface layer containing residue of vegetable crops, leading to an altered composition and the improved aeration of the soil's surface layer to enhance the decomposition of organic matter (Zhao et al. 2022). Hence, tillage practices should be considered to improve the land's productivity, as these require reduced effort and costs (Guimarães Júnnyor et al. 2019; Jha et al. 2012; Rodrigo-Comino et al. 2022; Souza et al. 2021).

The application of secondary-tillage equipment can lead to the deterioration of soil properties related to construction in the absence of optimal equipment selection, as this destroys the soil's cover and structure, and leads to soil erosion, increased moisture evaporation, and deactivation of lifecycles beneficial to soil organisms (Lamandé et al. 2023; Silva et al. 2021). This problem is more severe in soils that tend to form a hardened surface crust (Maffia et al. 2020; Zheng et al. 2023). For example, tillage can lead to an increase in the volume occupied by soil, which can cause changes in ρb due to compact soil caused by the repeated passage of agricultural machinery (Mesmin et al. 2020; Sang et al. 2016). This is notably important in soils with a weak structure (Lu et al. 2017; Ma et al. 2022; Rodrigo-Comino et al. 2020), as soil aggregates are subjected to fractures during rainfall or irrigation (Balota et al. 2016). This can lead to aggregate dispersal and the transfer of fine soil particles suspended within larger soil pores, clogging these and forming a hard crust on the soil's surface when dry. Its thickness ranges from a few millimeters to several centimeters (Chamizo et al. 2012; Chen et al. 2022). The soil's surface crust strongly affects water flow and reduces the hydraulic conductivity of the soil, which can lead to increased runoff and decreased water storage. Soil crust formation also leads to poor aeration, reducing the gas exchanges between soil, air, and the lower atmosphere (Jiang et al. 2018a; Zhu et al. 2018).

Conservation tillage (also known as till-plant (TP), no-tillage, or reduced tillage) involves the reduction of tillage processes and the use of agricultural equipment, leading to an improvement in soil properties due to reduced soil disturbance (Battaglia et al. 2023; Blanco-Canqui & Ruis 2018; Mirzaei et al. 2022) and maintenance of vegetation cover (Fernandes et al. 2023). This type of management also improves organic soil content (*SOC*) (Oliveira et al. 2022; Perego et al. 2018), soil penetration resistance (Bogunovic et al. 2018), soil water storage and infiltration (Guimarães Júnnyor et al. 2019), ρb (Tian et al. 2022a), crop yields (Guo et al. 2017; Obia et al. 2020), surface crusting (Gicheru et al. 2004), and MWD (Sarker et al. 2018). Furthermore, biodiversity is increased and carbon dioxide emissions are reduced, as it is an environmentally friendly technology that requires less fuel (Silva-Olaya et al. 2013). Thus, TP improves both soil properties and crop development.

Wheat cultivation in Iraq generally involves the use of organic manure (i.e., animal or plant), which is often recognized as useful for soil agri-structures (Fang et al. 2019). It can control *SC* formation (Tian et al. 2022b), increase SOC (Li et al. 2022; Miao et al. 2019), improve soil structural stability (Cui et al. 2023), and decrease ρb (Xin et al. 2016).

Additionally, organic manure affects water retention, increasing the soil's holding capacity and making it resistant to agricultural operations (Ding et al. 2021; Esmaeilian et al. 2022), which reduces the likelihood of forming *SCs* (Cui et al. 2023; Jiang et al. 2018b), and increases crop yields (Omara et al. 2017). Hence, the use of organic manure positively affects the soil's structural and water qualities and can control the degree of *SCs* hardness (Faist et al. 2017).

Most of central and southern Iraq is arid or semi-arid, with soils containing low percentages of organic matter. Most soils lack vegetation cover and poor irrigation practices lead to a deterioration in the soil's physical properties and surface crust formation, negatively impacting agricultural production.

The research question in this study focused on impact of tillage systems and organic manure on the soil's physical attributes of the Iraq, including as SCs, SPR, volumetric water content (VWC), ρb, and MWD of soil aggregates during wheat growth stages. In addition, little is known about the use of tillage practices without cultivation in the off-season and how these affect the soil's physical attributes for sustainable agricultural production. Furthermore, aggregate stability and irrigation of agricultural soil are major issues currently limiting sustainable agricultural production in the semi-arid Kut region. The use of appropriate tillage systems and manure application can therefore contribute effectively to control SCs, improving the soil's physical attributes and germination rates.

This article investigates the overall impact of tillage practices and organic manure applications on the formation of *SCs* and soil physical attributes (*SPR*, *VWC*, *ρb*, and *MWD*) during the growth stages of wheat. Furthermore, it determines the relationship between soil *ρb* and *SCs* and between *VWC* and *SPR*, under different agronomic practices in clay loam and clay soil.

2 Materials and methods

2.1 Experimental sites

This experiment was conducted between 2021 and 2022 during two field experiments in the Al Qataniyah village, which is located near the Aziziyah City in Kut, Iraq (32.91° N, 44.9° E), 82 km South of Baghdad and 3 km North of the Tigris River (Fig. 1). The distance between the two field sites is 8 km. The soils were classified mainly as Entisols (Soil Survey Staff 2014), according to the criteria determined by Muhaimeed et al. (2014). The first experiment was conducted at a site with clay loam soil that was previously planted with alfalfa (21% sand, 40% silt, and 39% clay at 0–25 cm), and the soil layer had an organic matter of 8.6 gm kg^{-1}, a soil dry *ρb* of 1.42 g cm^{-3}, a *pH* of 7.70, and an electrical conductivity (*EC)* of 3.81 Ds m^{-1} (Table 1).

The second experiment was conducted at a site with clay soil (Soil Survey Staff 2014) (20% sand, 30% silt, 50% clay at 0–30 cm soil depth) (Fig. 1) that was previously planted with maize. The soil layer had an organic matter of 6.8%, a soil dry *ρb* of 1.51 g cm^{-3}, a pH of 7.36, and an EC of 11.22 Ds m^{-1} (Table 1). Both fields are located within arid and semi-arid areas, 34.1 m a.s.l., where the annual average temperature is 45 °C. Winter wheat is a major crop in Kut City, which is planted in early October and harvested in June. This area has minimal rainfall, which leads to challenges with the use of irrigation techniques during the winter wheat season. Hence, surface irrigation via water pumps is widely used by domestic planters. Recently, the amount of precipitation has decreased due to climate change. The eight-month precipitation distribution and the cumulative amount of precipitation curves are shown in Fig. 2 and include the recorded amount of rainfall and the air temperature during this study. Rainfall was more abundant during winter between October and June, and gradually decreased until reaching its lowest level in April and May. Figure 2 also shows the average air humidity and temperature during wheat growth stages, as well as different instances of soil sampling across stages.

2.2 Management practices

This experiment investigated the effect of tillage systems and manure application on *SC* formation, soil physical attributes, and wheat production at two sites in Iraq. To control the presence of weeds, prior plowing and leveling were necessary. After irrigation, the land was divided into different

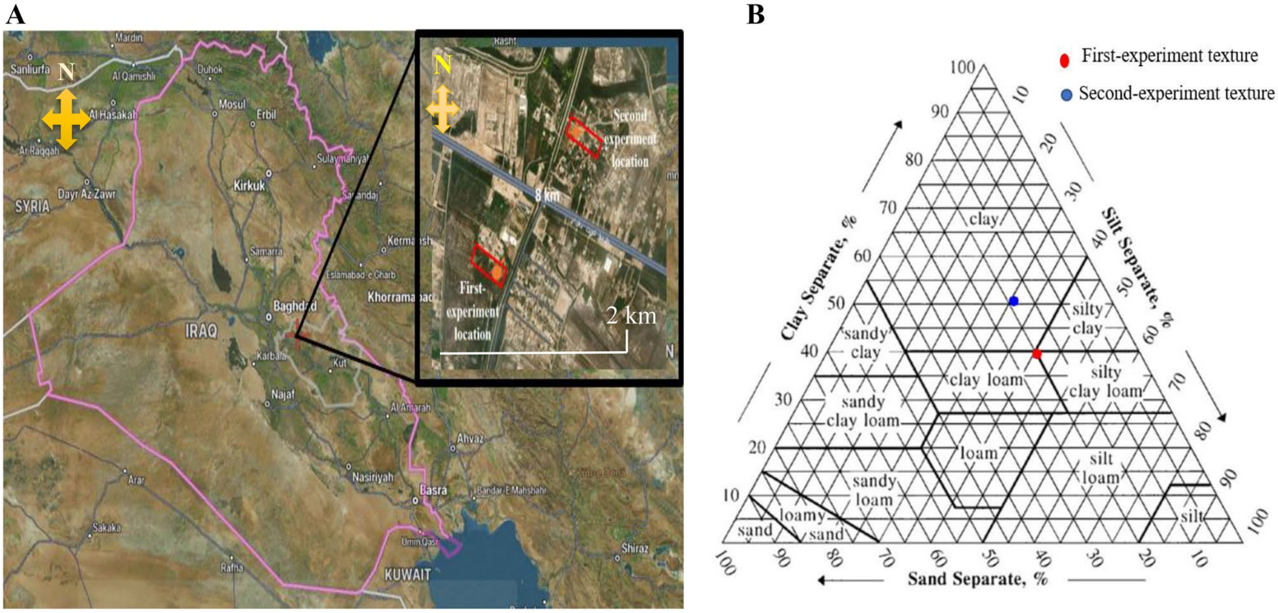


Fig. 1 **A** Location of the experimental sites. **B** Triangle texture of the two field experiments

Table 1 Soil characteristics of the two experimental sites

Site ID		First-experiment soil	Second-experiment			
Soil depth		0–25cm	0–25 cm			
Soil water content (θ; %)		28.6	21			
Soil organic matter (*SOM*; %)		8.6	6.8			
Soil dry bulk density (ρb; g cm^{-3})		1.42	1.51			
Soil particle density (D_p; g cm^{-3})		2.64	2.64			
pH		7.7	7.36			
EC Ds m^{-1}		3.81	11.22			
CEC cmol(+) kg−1		28.15				
Particle size distribution	Clay	340	500			
g kg^{-}	Silt	400	300			
	Sand	260	200			
Soil texture		Clay loam	Clay			
Chemical analysis of cattle manure used in the current study						
pH	OM	Total organic carbon	Total nitrogen	K	P	C:N
7.3	69.6	41	1.9	1.6	0.73	23.4

tillage system treatments and manure applications, after which the study was performed.

The experiential design in both fields was identical, and a randomized complete block design (RCBD) was used, where a nested-factorial experimental design was used. There were 9 different treatments with three replicates each, resulting in a total of 27 soil treatments at each site (Fig. 3). All plots were 20 m wide and 60 m long (1200 m^2), with a 1 m spacing between plots. The obtained results were statistically analyzed using the least significant difference (LSD) method at a 0.05 probability level. The procedures were distributed as follows:

- The main treatment included three tillage practices:

1 CT: soil preparation involved the use of a Moldboard plow (MP) and a single pass of rotary harrowing (RH),

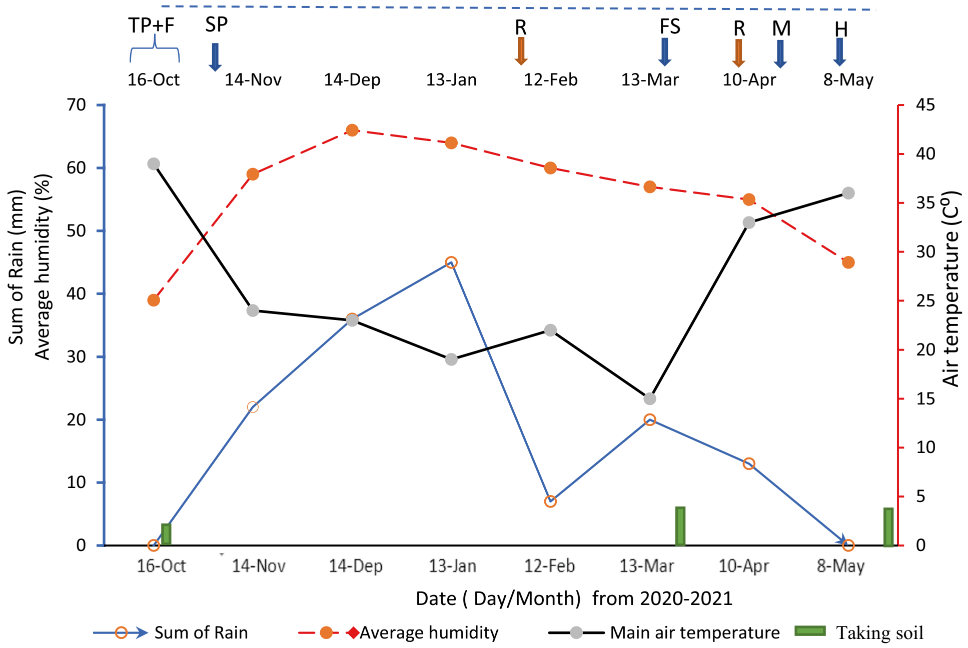


Fig. 2 The sum of rain, average air humidity, and average air temperature during the management of wheat growth stages in 2021–2022. A green dashed line is used to mark the soil samples taken during different stages. TP+FP: tillage practices plus fertilizer applications stage; SP: seed planted; R: irrigation; FS: flowering stage; M: mature; H: crop harvested

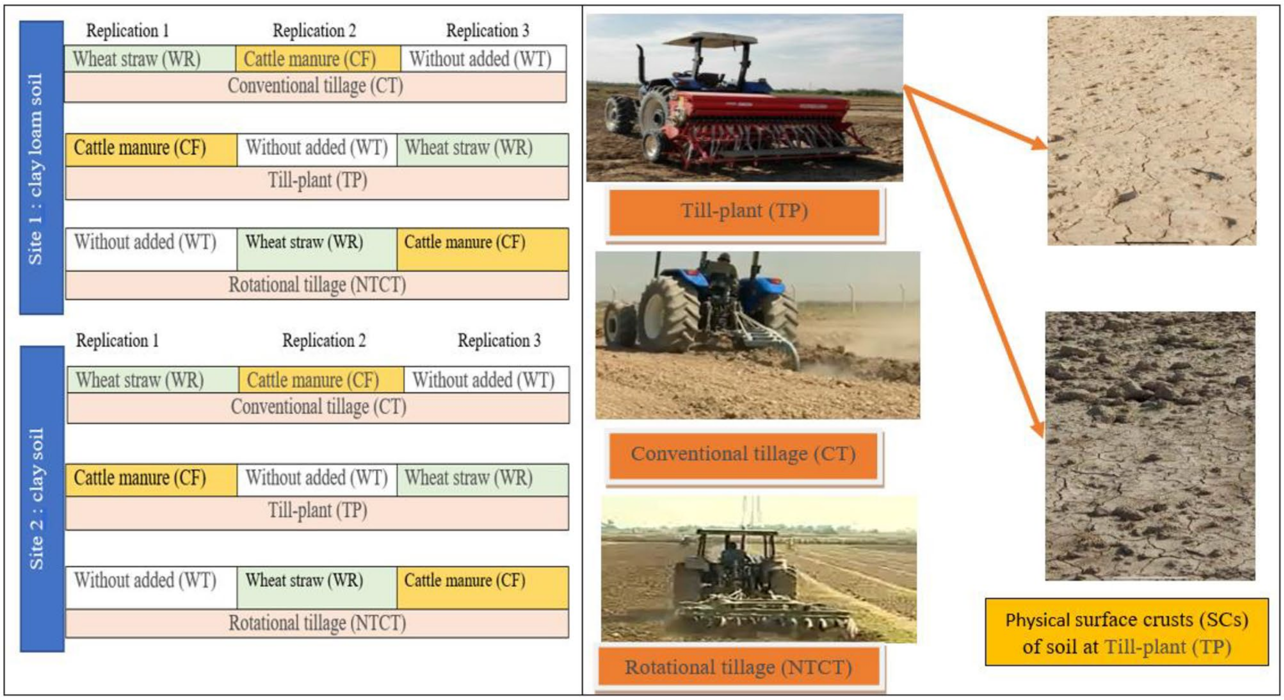


Fig. 3 Flow chart of the experimental field layout and photos of each tillage practice used in the present study. Physical surface crusts (SCs) of soil at Till-plant (TP)

followed by leveling with crop residue removal for more than 5 years.

2 TP (CT using a MP and two passes of RH at 25–30 cm soil depth in October 2019, with no subsequent tillage): this treatment requires seeds to be planted in tight slits within the soil using a wheat seed-fertilizer drill machine with 11 furrow openers and 11 press wheels. Given that the alfalfa growing season occurred in October 2019, alfalfa was used as a natural soil fertilizer, with one or two cuttings harvested at a time. During harvesting, most of the alfalfa is removed, but some remains on the soil's surface. At the end of the season, the land is furrowed and the remaining alfalfa is mixed into the soil to improve its physical and chemical properties, thereby preventing the field from being subjected to mechanical treatment or the passage of equipment haulers. Hence, the soil of this field was left in a stable state.

3 Rotational tillage (NTCT, two years of no tillage (NT) and 1 year of CT using disc plowing and a single pass of RH).

- The sub-treatment included three fertilizer applications:

1 Animal manure: the soil was treated with cattle manure (CF; 12,500 kg ha^{-1}).

2 Plant manure: The soil was treated with wheat straw (WR;10,000 kg ha^{-1}).

3 Control treatment: No fertilizer was added (WT).

Tillage practices were applied to the soil at both locations as the main plot factor. For the CT plot, the soil was plowed by a tractor-mounted MP (Supplementary information Doc and Table 1) to a depth of 20–25 cm, followed by a secondary seedbed preparation by RH (smooth edge disc) to a depth of 10–15 cm. A field cultivator was then used to level and harden the plots before wheat planting. In the TP plot, a wheat seed-fertilizer drill machine was utilized for wheat planting. Here, the drill consisted of 10 opener units arranged 20 cm apart, giving a working width of 220 cm. The machine also included a fertilizer unit, a drill hitch, and seed furrow openers (Supplementary information Doc and Table 1). Wheat straw and plant residues were removed in all TP treatments using hand hoes. This tillage method destroyed the soil's surface crusts, but these were speedily re-established after rainfall, as has been shown by (Gicheru et al. 2004). The till and sowing depth obtained above were of 10–15 cm. The NTCT rotation tillage included two years of NT and 1 year of conventional tillage using a disc plow and RHs during primary and secondary tillage, after which wheat planting could occur.

For CF and WR treatments, the soil was treated with these after the volumetric soil water content was 20%.

12,500 kg ha^{-1} of CF and 10,000 kg ha^{-1} of WR were distributed on the surface of the soil homogeneously and then mixed with the surface layer using a hand rake. The chemical analysis of the cattle manure used is presented in Table 1.

2.3 Soil samples

Soil samples were collected at both locations from tillage to harvesting stages. These include, as described below:

1. Soil samples were collected at randomly selected locations within the experimental area to estimate the soil's chemical, physical, biological, and fertility characteristics, as shown in Table 1.
2. Soil samples were collected from each experimental unit at 0–15 cm depth after the applied land management stage, which consisted of tillage systems and FA (stage 1, 20–22 October 2021), to estimate the soil's SCs, soil compaction or *SPR*, *VWC*, *ρb*, and *MWD* of aggregates.
3. Soil samples were collected from each experimental unit at the beginning of the flowering stage (stage 2, 20–23 March 2022) to estimate the *SCs*, *SPR*, *VWC*, *ρb*, and *MWD*.
4. Soil samples were collected from each experimental unit at the end of the season during the post-harvest stage (stage 3, 25–26 May 2022) to estimate the *SCs*, *SPR*, *VWC*, *ρb*, *MWD*, and *WP*.

2.4 Wheat planting and irrigation

Wheat (*Triticum aestivum* L.) type 22 was obtained from the Agricultural Research Department/Grain Crops Department. For TP plots, grains were planted in lines on the 15th of November 2021 with a seeding rate of 140 kg ha^{-1} using a wheat seed-fertilizer drill machine. For CT and NTCT plots, grains were planted in lines on the same date, and seeds were covered using a spike tooth harrow.

Irrigation was carried out by bringing each experimental unit to its maximum water-holding capacity by adding the required volume of water to it at a specific time. This was done as described: (1) soil samples were collected from each experimental unit before irrigation, and the weight percentage of moisture (θ_{w1}) was estimated; (2) moisture content at field capacity was determined based on the water retention curve (θ_{w2}); (3) moisture content by weight to be reached θ_w was determined by the equation: $\theta_{w2} - \theta_{w1}$; (4) volumetric water content θ_w was calculated by the equation: $\theta_w * \rho b$; (5) water depth (D; cm) was calculated for each treatment by: $D = \theta w * d$, where d is the root zone depth in cm; (6) water volume (v; m^3) to be added was determined by the equation: $v = D * A$, where A is the treatment area; and (7) irrigation time for each treatment was calculated by the equation: $t = v/Q$, where Q is pump capacity (m^3 sec^{-1}). Samples of wheat were manually harvested for an area of 5 × 1 m for yield assessment.

2.5 Agronomic parameters used in the study

The soil's physical properties (*SCs, SPR*, texture, *VWC*, *ρb*, and *MWD*) of aggregates for both field experiments were measured. *SCs* were determined by Vernier (Shi et al. 2023), while *SPR* was measured by a Pocket Penetrometer, which can measure the shear strength of soil between 0–5 kg cm^{-2} (Yasun 2018). Mechanical analysis of the soil's field sites measured soil textures using a hydrometer (Mwendwa 2022). *VWC* was determined based on dry weight, accomplished via oven-drying at 105 °C for 24 h according to a method described by Szypłowska et al. (2021). The *ρb* and soil water content (θ) were determined for both fields using a digital electromechanical system (DES), and by soil core samples (Al-Shammary et al. 2019). Particle density (D_p) was measured by the pycnometer method (Ruehlmann & Körschens 2020). The soil's organic matter (SOM) was measured by the loss on ignition method (Jackson 2005), while the soil's pH and electrical conductivity (EC) were measured in 1:1 water extracts using a pH meter (type; HACH\HQ 41-1d), and an EC meter (type; HACH\EC71), respectively. Cation exchange capacity (CEC) was analyzed using the simplified methylene blue method (Savant 1994). Finally, the MWD was determined for each soil treatment by wetting 25 g of dry soil aggregates for 6 min by the capillary method (ranging from 4 to 9 mm). The samples were then sieved with 4.75, 2.36, 1.00, 0.50, and 0.25 mm sieves from top to bottom, dried at 105 °C and weighed. The stability of soil agglomerations was expressed by the weighted diameter ratio according to the following equation (Xia et al. 2022):

$$\mathrm{MWD} = \sum_{i=1}^{n} wixi$$

where *wi* is the remaining aggregate weight of soil sample particles in the sieve (g) and *xi* is the aggregate average particle size of the top and bottom sieves (mm).

At the harvesting stage, grain sampling and analysis of the wheat yield were conducted. Three random squares within each plot, each with an area of 1 × 2 m, were used to gather the grain biomass of wheat. After air drying, the wheat was mechanically detached from straw and harvested by an electric grain extractor. The grain was then heated at 65 °C for 2 days, and the dry grain weight was calculated to determine wheat production.

2.6 Statistical analysis

The experiential design in both fields was identical, and a randomized complete block design (RCBD) and a nested-factorial experimental design were used. SCs, SPR, texture, VWC, ρb, and MWD of aggregates for both field experiments were tested. The two-way ANOVA analysis, coefficient of variation (CV) and coefficient of determination (R^2), were carried out using SAS 9.4v (SAS 2013).

3 Results and discussion

3.1 Soil surface crusts (*SCs*)

The impact of tillage practices and FA on the *SCs* of soils after land management, flowering, and post-harvest stages at both field experiment sites are summarized in Fig. 4 and Tables 2 and 3.

In the experiment on clay loam soil, the comparison of agronomic practices used as CT, TP, and NTCT during the wheat growth stages showed a significant difference ($p<0.05$) in the average *SCs* of soil during post-tillage, flowering, and post-harvest stages. Namely, in all soil treatments plowed by CT, the *SCs* were significantly higher at 0.79, 0.83, and 0.86 cm during the post-tillage, flowering, and post-harvest stages, respectively. On the other hand, the NTCT system showed the lowest *SCs* at 0.48, 0.51, and 0.58 cm during each of the wheat growth stages, respectively (Fig. 4a–c). However, there was a descending trend in SCs with the reduction of tillage by TP and NTCT for all soil treatments across wheat growth stages, which could explain why NTCT had more stable aggregates than CT and TP plots with both soil textures. This result may be explained by the fact that aggregate stability decreased alongside the reduced compaction that occurs in the soil due to mechanical forces that can affect the soil's surface. Therefore, management practices with NTCT had the lowest risk of crust formation, which is consistent with other recent studies (Wuest & Schillinger 2022; Yuan et al. 2022; Zhao et al. 2022).

On the other hand, in the same experiment, FA significantly affected *SCs*. Under the CF treatment, *SCs* decreased by an average of 0.52 cm at post-tillage, 0.57 cm at the flowering stage, and 0.62 cm at post-harvest, while *SCs* increased by an average of 0.77 cm at post-tillage, 0.80 cm at flowering stage, and 0.87 cm at post-harvest without added fertilizer (WT; Fig. 4a–c). Thus, the greatest reduction in *SCs* occurred when organic fertilizer was added during growth stages, resulting in a more modest reduction of *SCs*.

In the second experiment with clay textured soil, regardless of the statistical equality, tillage treatments resulted in a significant difference in *SCs*. CT showed the highest

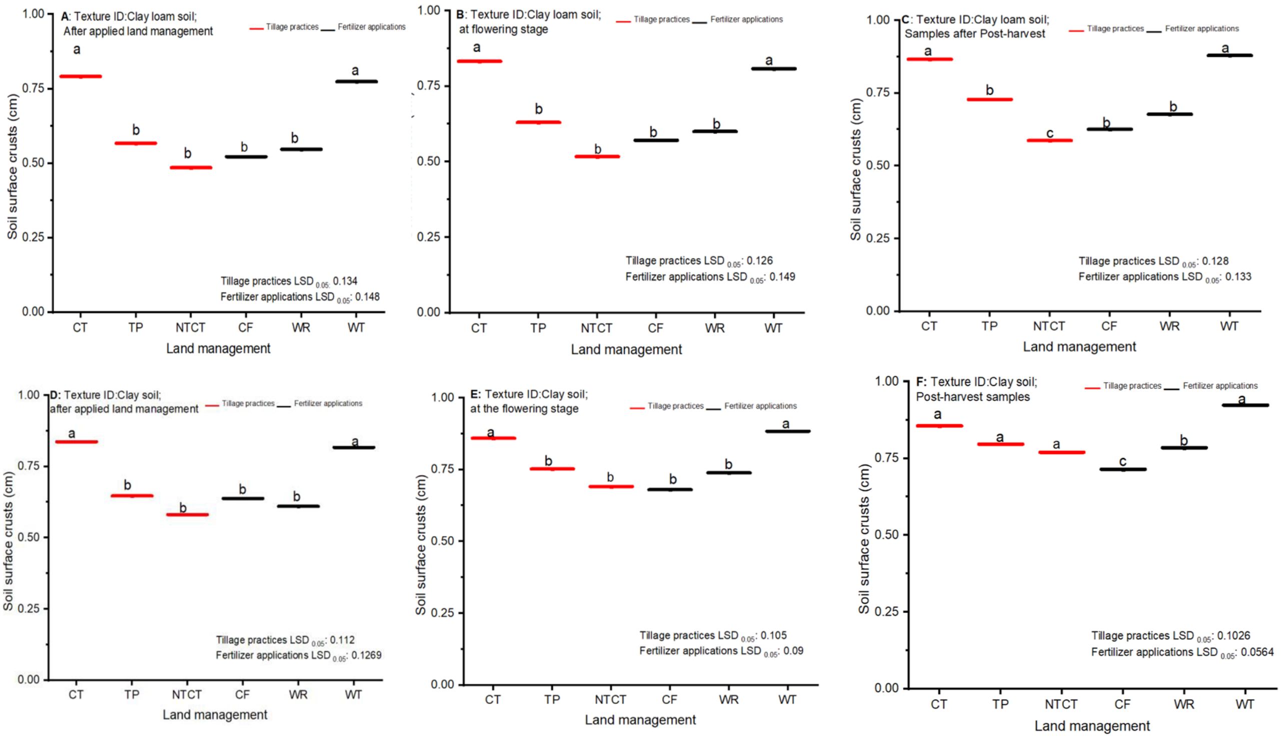


Fig. 4 Soil surface crusts of the clay loam/clay soil at post-tillage, flowering, and post-harvest stages with different agronomic practices. CT: conventional tillage by Moldboard plow + single pass of rotary harrowing. TP: Till-plant using a wheat seed fertilizer drill machine. NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing. CF: cattle manure; WR: wheat straw; WT: without added fertilizer. The same letters above the histograms indicate no significant difference at $p>0.05$, while different letters indicate significant differences at the 0.05 level. The line in the figures shows the mean (mean: $n=9$)

Table 2 Soil surface crusts, soil compaction, soil water conservation, soil bulk density, and mean weight diameter of aggregates of the clay loam, under the interactive effect of tillage practices and fertilizer applications at A: tillage stage, B: flowering stage, C: post-harvest stage; CT: conventional tillage by Moldboard plow + single pass of rotary harrowing; TP: Till-plant using a wheat seed fertilizer drill machine; NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing; CF: cattle manure; WR: wheat straw; WT: without added fertilizer

Land management		Soil surface crusts	Soil compaction	Soil water conservation	Soil bulk density	Mean weight diameter of aggregates
Tillage practices	Fertilizer applications	cm	kPa	$cm^3\ cm^{-3}$	$g\ cm^{-3}$	mm
A. Tillage stage						
CT	CF	0.66^{c}	230^{b}	0.180^{bc}	1.38^{bc}	0.178^{d}
CT	WR	0.78^{b}	242^{b}	0.116^{ed}	1.43^{b}	0.143^{e}
CT	WT	0.93^{a}	275^{a}	0.076^{e}	1.53^{a}	0.095^{g}
TP	CF	0.57^{d}	142^{e}	0.236^{a}	1.26^{e}	0.241^{b}
TP	WR	0.43^{e}	167^{d}	0.203^{ab}	1.30^{de}	0.216^{c}
TP	WT	0.70^{c}	202^{c}	0.116^{ed}	1.36^{cd}	0.127^{f}
NTCT	CF	0.43^{f}	208^{c}	0.166^{cd}	1.20^{f}	0.273^{a}
NTCT	WR	0.43^{e}	242^{b}	0.143^{cd}	1.26^{e}	0.237^{g}
NTCT	WT	0.69^{c}	279^{a}	0.113^{ed}	1.31^{de}	0.174^{d}
Mean		0.61	221.0	0.150	1.34	0.18
$LSD_{0.05}$		0.07	12.9	0.05	0.05	0.01
R^2		0.96	0.98	0.77	0.91	0.98
CV		7.00	3.40	21.00	2.50	3.90
B. Flowering stage						
CT	CF	0.71^{c}	231^{b}	0.343^{b}	1.35^{cd}	0.191^{d}
CT	WR	0.82^{b}	239^{b}	0.290^{c}	1.44^{b}	0.172^{d}
CT	WT	0.96^{a}	270^{a}	0.223^{d}	1.51^{a}	0.129^{e}
TP	CF	0.62^{d}	138^{e}	0.370^{ab}	1.31^{d}	0.255^{b}
TP	WR	0.51^{d}	164^{d}	0.350^{b}	1.32^{d}	0.231^{c}
TP	WT	0.75^{bc}	194^{c}	0.250^{cd}	1.38^{bc}	0.140^{e}
NTCT	CF	0.37^{f}	188^{c}	0.403^{a}	1.24^{ef}	0.292^{a}
NTCT	WR	0.46^{e}	230^{b}	0.360^{ab}	1.22^{f}	0.253^{bc}
NTCT	WT	0.71^{cd}	263^{a}	0.280^{c}	1.30^{de}	0.184^{d}
Mean		0.65	213.0	0.31	1.34	0.205
$LSD_{0.05}$		0.09	16.10	0.05	0.05	0.02
R^2		0.94	0.96	0.85	0.89	0.95
CV		7.70	4.40	9.10	2.60	6.60
C: post-harvest						
CT	CF	0.74^{cbd}	242^{b}	0.243^{bc}	1.36^{bcd}	0.197^{d}
CT	WR	0.83^{b}	240^{b}	0.206^{cd}	1.42^{b}	0.179^{e}
CT	WT	1.02^{a}	280^{a}	0.120^{e}	1.57^{a}	0.110^{g}
TP	CF	0.68^{dc}	147^{f}	0.313^{a}	1.35^{bcd}	0.242^{c}
TP	WR	0.66^{d}	172^{e}	0.243^{bc}	1.35^{cd}	0.234^{c}
TP	WT	0.83^{b}	203^{d}	0.180^{d}	1.40^{bc}	0.134^{f}
NTCT	CF	0.44^{e}	212^{cd}	0.250^{b}	1.31^{de}	0.284^{a}
NTCT	WR	0.53^{e}	222^{c}	0.196^{d}	1.27^{e}	0.257^{b}
NTCT	WT	0.78^{bc}	273^{a}	0.200^{d}	1.33^{de}	0.181^{e}
Mean		0.72	221.4	0.217	1.37	0.202
$LSD_{0.05}$		0.10	15.04	0.04	0.07	0.01
R^2		0.91	0.97	0.87	0.85	0.98
CV		8.30	4.00	10.70	3.00	3.90

Means followed by the same letters above the numbers on the line are not significantly different at $p > 0.05$, using Tukey's HST test, while different letters indicate significant differences at the 0.05 level

R^2 coefficient of determination, *CV* coefficient of variation

Table 3 Soil surface crusts, soil compaction, soil water conservation, soil bulk density, and mean weight diameter of aggregates of the clay soil, under the interactive effect of tillage practices and fertilizer applications at A: tillage stage, B: flowering stage, C: post-harvest stage; CT: conventional tillage by Moldboard plow + single pass of rotary harrowing; TP: Till-plant using a wheat seed fertilizer drill machine; NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing; CF: cattle manure; WR: wheat straw; WT: without added fertilizer

Land management		Soil surface crusts	Soil compaction	Soil water conservation	Soil bulk density	Mean weight diameter of aggregates
Tillage practices	Fertilizer applications	cm	kPa	cm^3 cm^{-3}	G cm^{-3}	mm
A. Tillage stage						
CT	CF	0.75^{bc}	249.3dc	0.35^{ab}	1.38^{cde}	0.27^{de}
CT	WR	0.81^{b}	266.6bcd	0.29^{c}	1.38^{de}	0.23^{e}
CT	WT	0.94^{a}	327.3a	0.26^{c}	1.36^{e}	0.13^{f}
TP	CF	0.64^{d}	189.6f	0.36^{ab}	1.46^{a}	0.70^{a}
TP	WR	0.48^{e}	176.6f	0.33^{b}	1.46^{a}	0.54^{b}
TP	WT	0.81^{b}	219.0e	0.25^{c}	1.43^{ab}	0.32^{d}
NTCT	CF	0.52^{e}	245.6d	0.37^{a}	1.40^{cde}	0.40^{c}
NTCT	WR	0.53^{e}	271.6bc	0.38^{a}	1.41^{bcd}	0.31^{d}
NTCT	WT	0.69 ^{cd}	290.3b	0.25^{c}	1.43^{abc}	0.14^{f}
Mean		0.68	248.4	0.31	1.41	0.34
LSD $_{0.05}$		0.08	24.60	0.04	0.05	0.05
***R*^{2}**		0.94	0.94	0.89	0.74	0.98
CV		7.00	5.70	7.00	1.90	9.20
B. Flowering stage						
CT	CF	0.74^{d}	266.0^{dc}	0.32^{bc}	1.39^{c}	0.27e
CT	WR	0.86^{bc}	275.6^{bc}	0.28^{de}	1.41^{c}	0.24ef
CT	WT	0.96^{a}	365.0^{a}	0.26^{e}	1.45^{ab}	0.14 g
TP	CF	0.63^{e}	192.6^{e}	0.38^{a}	1.42^{bc}	0.75a
TP	WR	0.74^{d}	250.3^{dc}	0.34^{b}	1.38^{c}	0.59b
TP	WT	0.87^{b}	272.3^{bc}	0.31 ^{cd}	1.42^{bc}	0.37d
NTCT	CF	0.66^{e}	244.6^{d}	0.35^{ab}	1.45^{ab}	0.45c
NTCT	WR	0.60^{e}	192.6^{e}	0.33^{bc}	1.46^{a}	0.37d
NTCT	WT	0.80^{dc}	292.3^{b}	0.28^{de}	1.49^{a}	0.18 fg
Mean		0.76	261.2	0.31	1.42	0.37
LSD $_{0.05}$		0.07	26.20	0.03	0.04	0.07
***R*^{2}**		0.93	0.94	0.88	0.77	0.97
CV		5.10	5.70	5.10	1.60	11.10
C. Post-harvest						
CT	CF	0.74 ^{cd}	276.6^{bc}	0.29^{abc}	1.41^{c}	0.29^{e}
CT	WR	0.87^{b}	291.0^{b}	0.23^{de}	1.43^{bc}	0.25^{e}
CT	WT	0.95^{a}	383.3^{a}	0.20^{e}	1.47^{ab}	0.16^{f}
TP	CF	0.68^{e}	212.6^{e}	0.33^{a}	1.44^{bc}	0.77^{a}
TP	WR	0.77^{c}	257.0 ^{cd}	0.28^{bc}	1.43^{bc}	0.66^{b}
TP	WT	0.92^{ab}	289.0^{b}	0.20^{e}	1.44 ^{cd}	0.44 ^{cd}
NTCT	CF	0.71^{ed}	181.6^{f}	0.30^{ab}	1.43^{bc}	0.49^{c}
NTCT	WR	0.70^{ed}	244.6^{d}	0.25 ^{cd}	1.46^{ab}	0.42^{d}
NTCT	WT	0.89^{b}	299.0^{b}	0.20^{e}	1.50^{a}	0.25^{e}
Mean		0.80	270.5	0.256	1.44	0.41
LSD $_{0.05}$		0.05	23.30	0.04	0.05	0.05
***R*^{2}**		0.94	0.96	0.85	0.55	0.98
CV		3.90	4.90	9.90	1.90	7.30

Means followed by the same letters above the numbers on the line are not significantly different at $p > 0.05$, using Tukey's HST test, while different letters indicate significant differences at the 0.05 level

R^2 coefficient of determination, *CV* coefficient of variation proportion of *SCs* (0.83, 0.83, and 0.85 cm at post-tillage, flowering, and post-harvest stages, respectively), when compared to TP and NTCT systems, which showed the lowest *SCs*. In addition, there was no significant effect ($p < 0.05$) for TP and NTCT systems on *SCs* for all soil treatments, or during wheat growth stages (Fig. 4d–f). The effect of fertilizer addition, both CF and WR, on the *SCs* of clay soil showed only a slight difference in *SCs* over time in post-tillage, flowering, and post-harvest stages. Furthermore, it was observed that the water content during sampling of each stage influenced the formation of *SCs*. This was due to the ability of CT to improve the *SOC*, which led to preventing the soil aggregates from collapsing and increasing microbial respiration. Thus, the quantity of *SCs* was reduced in the soil suspension, and the structural stability of soils was improved within the experimental site, which subsequently reduced the thickness of the surface crust formed from the sedimentation of these materials (Cui et al. 2023; Greenwood 2021; Lian et al. 2022).

Based on the above findings, this study indicated that soil textures influence the formation of *SCs*, with the percentage of clay-sized particles in the second experiment increasing trend when *SC* formation began. The reason for this phenomenon is related to the spread of clay particles and the formation of a highly concentrated suspension, which led to a thicker layer being formed during drought, which was consistent with a recent study (Li et al. 2023). Moreover, an increase in soil ρb in both soil textures led to an increase in the formation of *SCs* for all treatments used in the experiment, with a significant correlation ($r = 0.85$ and $R^2 = 0.73$ for clay loam; $r = 87$ and $R^2 = 0.75$ for clay) between *SCs* and ρb (Fig. 5a, b). Consequently, the distribution of *SCs* using the NTCT system was shown to be promising over time, and the CF application had the least impact on the formation of *SCs*.

There was a considerable effect of tillage practice and FA ($p < 0.05$) on *SCs* over time in the post-tillage, flowering, and post-harvest stages for both soil textures (Tables 2 and 3). For example, the *SCs* of clay loam showed an interactive effect between CT and WT, resulting in greater *SCs* of 0.93 cm in the post-tillage stage, 0.96 cm in the flowering stage, and 1.02 cm in the post-harvest stage when compared to other soil treatments (Table 2). For clay texture, *SCs* ranged from 0.48 to 0.94 cm for (TP × WR) and CT × WT, respectively, during the tillage stage. During the flowering stage, *SCs* ranged from 0.60 to 0.96 cm for NTCT × WR and CT × WT, respectively, which significantly differed from other soil treatments. In the post-harvest stage, *SCs* ranged from 0.68 to 0.95 cm for TP × CF and TP × WT, respectively (Table 3). The results included in Tables 2 and 3 indicated that variations (CV) in *SC* values for soil treatments across wheat growth stages for both soil textures could be attributed to variations in the effect of tillage practices and FA. Interestingly, *SCs* were influenced by all land management techniques studied, which affected seedling emergence and associated wheat yields at both sites.

3.2 Soil penetration resistance (*SPR*)

SPR curves established for different agronomic practices used across three stages (post-tillage, flowering, and post-harvest) and two soil textures are presented in Fig. 6 and Tables 2 and 3. *SPR* values showed no significant differences ($p < 0.05$) among soil tillage treatments in clay loam soil at the post-tillage stage under the TP and NTCT systems, but there were significant differences with CT during the post-tillage stage. All treatments showed similar results at the flowering stage and during the post-harvest stage (Fig. 6a–c). Generally, *SPR* values decreased with conventional tillage and then increased over time. The highest

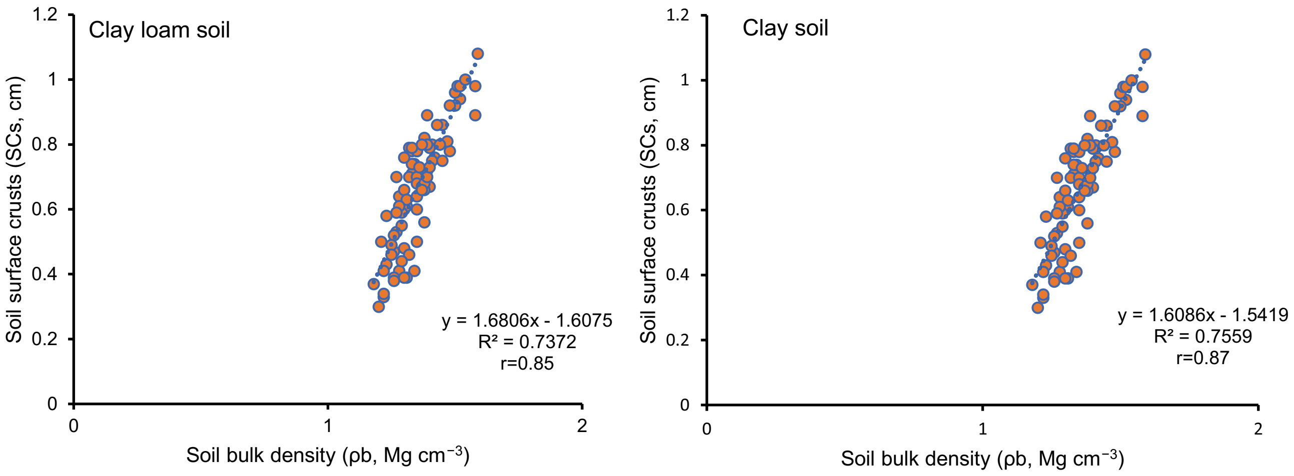


Fig. 5 Relationship of soil bulk density (*ρb*) and soil surface crusts (SCs) in two soil textures

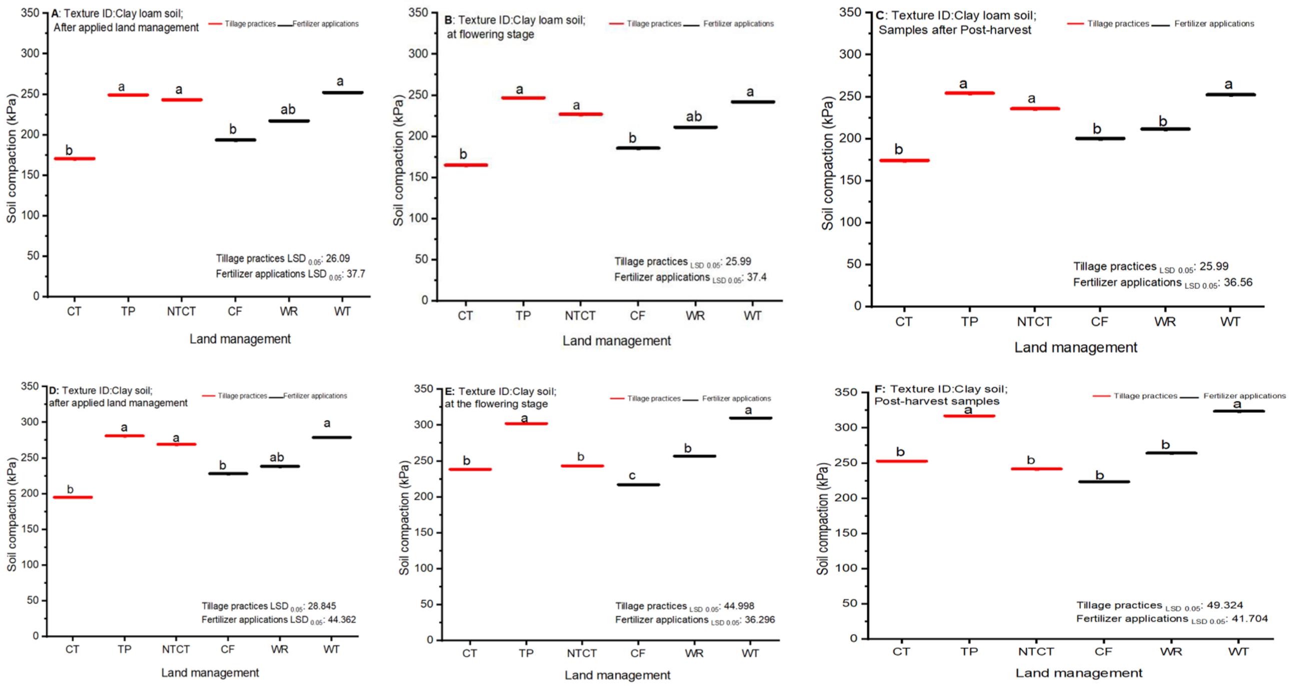


Fig. 6 Spatial variability in soil penetration resistance (SPR) of the clay loam/clay soil in the post-tillage, flowering, and post-harvest stages with different agronomic practices CT: conventional tillage by Moldboard plow + single pass of rotary harrowing. TP: Till-plant using a wheat seed fertilizer drill machine; NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing; CF: cattle manure; WR: wheat straw; WT: without added fertilizer. The same letters above the histograms indicate no significant difference at $p > 0.05$, while different letters indicate significant differences at the 0.05 level. The line in the figures shows the mean (mean: $n = 9$)

average *SPR* values were found with the TP system at the post-tillage stage (249 kPa), followed by the flowering stage (246.8 kPa), and the post-harvest stage (254.33 kPa). The lowest *SPR* values were found with the CT system, which showed results of 170.6, 165.1, and 174.2 kPa during the post-tillage, flowering, and post-harvest stages, respectively (Fig. 6a–c). This is due to CT and NTCT receiving no mechanical disturbance, as well as the interactive effect of pH and water conservation of soil. These results corroborate those of (de Moraes et al. 2016; de Oliveira et al. 2020; Guan et al. 2015; Li et al. 2020; Tian et al. 2022a), who found that CT affects the soil's structure, resulting in changes in *SPR* values and age-hardening phenomena.

Moreover, Fig. 6 shows that fertilizer use had a statistically important ($p < 0.05$) influence on *SPR* across all stages. The lowest levels of *SPR* seen during the post-tillage, flowering, and post-harvest stages of wheat growth were found under CF treatment (193.67, 185.78, and 200.33 kPa, respectively). However, WR had no significant effect on *SPR*. In the second experiment with clay soil, average values of *SPR* also showed no significant differences among CT and NTCT treatment systems. However, TP treatment showed lower *SPR* values over time at the post-tillage, flowering, and post-harvest stages (195, 170.6, and 241 kPa, respectively). The differences obtained for *SPR* across different wheat growth stages and soil textures are explained by the various organic fertilizer contents added to the soil, as a difference in *ρb* and water content may cause differences in *SPR* (Celik et al. 2010; Fang et al. 2021). Other studies have similarly reported that increased soil organic matter content led to reductions in *SPR* and *ρb*. In addition to the relationship between soil volumetric water content and *SPR*, *SPR* was directly affected by water content and inversely proportional to R^2 values (0.20 and 0.30 for clay loam and clay soils, respectively; Fig. 7a, b).

Soil texture largely determined *SPR*, as it was found that soil with a clay texture had the highest average values of *SPR* when compared to the soil with a clay loam texture, both of which were measured at three sampling stages. This is due to an increase in the percentage of clay leading to a rise in *SPR*, increasing the soil's water content (Oliveira et al. 2022; Souza et al. 2021).

In clay soil (Fig. 6d–f), *SPR* increased more at the post-harvest stage when compared with the post-tillage and flowering stages for both soil textures. However, *SPR* values were different for different wheat growth stages (Table 3). The highest *SPR* values were acquired with WT treatment, followed by WR and CF fertilizer applications for both soil

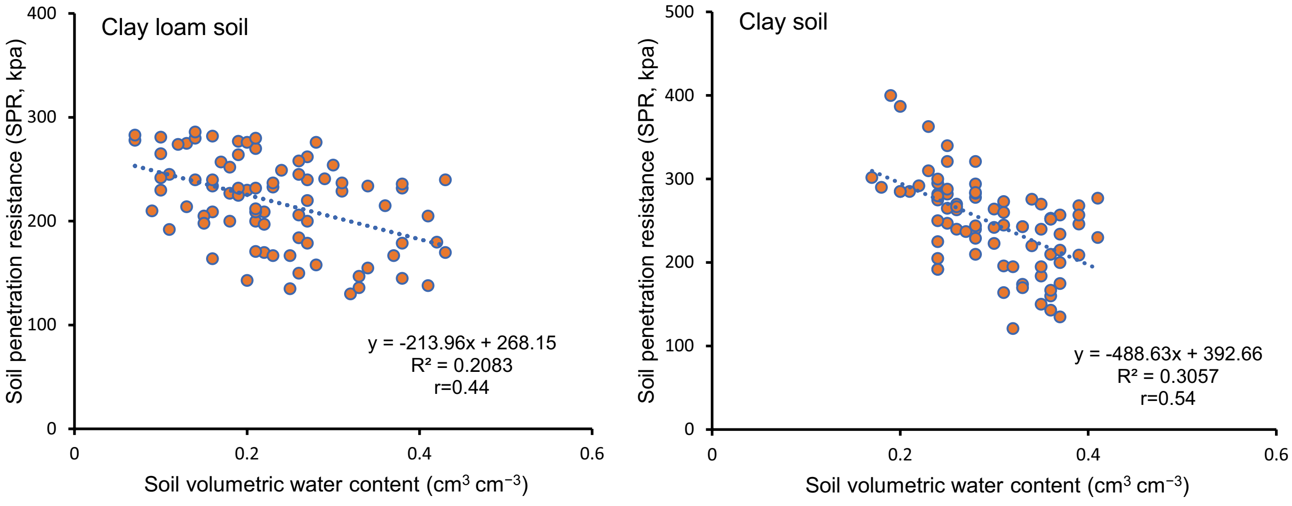


Fig. 7 Relationship between soil volumetric water content and penetration resistance for two soil textures

textures, respectively. A similar explanation to that of clay loam texture has been shown. Furthermore, the interaction between tillage practices and FA resulted in significant differences during the tillage, flowering, and post-harvest stages for both soil textures (Tables 2 and 3). For clay loam soil, the highest average *SPR* was found with 279, 270, and 280 kPa for NTCT × WT at the tillage stage, TP x WT at the flowering stage, and TP × WT at the post-harvest stage, respectively. In comparison with clay soil, TP × WT resulted in the highest *SPR* values with 327, 365, and 383 kPa for the tillage, flowering, and post-harvest stages, respectively. *SPR* significantly decreased as the organic content of the soil increased.

Results showed that *SPR* for both sites was positively and strongly correlated to tillage practices and FA during the tillage, flowering, and post-harvest stages (R^2 of clay loam: 0.98, 0.96, and 0.97, respectively; R^2 of clay soil; 0.94, 0.94, and 0.96, respectively). The majority of *SPR* values were lower for the clay loam soil than for the clay soil across different soil treatments and growth stages, as shown in Tables 2 and 3.

3.3 Volumetric water content (*VWC*) of soil

The distribution of *VWC* in the soil's surface (0–10 cm) with different land management practices and sampling periods (i.e., at post-tillage, flowering, and post-harvest) of both soil textures (clay loam, clay) is presented in Fig. 8 and Tables 2 and 3. For the clay loam soil, there was a significant influence of tillage practices used across all growth stages on the *VWC* ($p < 0.05$) with TP and CT, but not between TP and NTCT. *VWC* values for both post-tillage and post-harvest were significantly higher in the CT system when compared to the TP and NTCT systems (0.185 > 0.124 > 0.141 $cm^3 cm^{-3}$, respectively, at post-tillage stage; 0.245 > 0.190 > 0.215 $cm^3 cm^{-3}$, respectively, at post-harvest stage). Reduced *VWC* in the TP and NTCT systems for all soil sample stages could be due to the significantly higher ρb in the TP condition and because NTCT had lower pore-space (Acharya et al. 2019; Alexander et al. 2023; Nandan et al. 2019; Rajanna et al. 2022). Another possible explanation for this is the minimal runoff in the TP and NTCT conditions due to low precipitation or a low irrigation application rate. Other studies (Acharya et al. 2019; Nafi et al. 2020; Yost et al. 2023) have reported that *VWC* values were lower under no-tillage systems than they were under CT, due to minimum soil mechanical disturbance leading to restrictions in organic content oxidation.

With the same soil texture, the effect of FA on *VWC* increased with CF and WF treatments (Fig. 8, Table 3), when compared to WT (control). *VWC* was not found to be significantly ($p \leq 0.05$) different between CF and WF, while both were significantly higher than WT at the tillage stage, which is attributed to increased amounts of organic content present in CF when compared to WR and WT treatments (Traoré et al. 2004; Yost et al. 2023; Yue et al. 2022). Regarding the effect of soil management treatments for soil with clay textures, there was no significant effect of tillage practices on *VWC* ($p < 0.05$) at the post-tillage, flowering, or post-harvest stages. The greatest increase in *VWC* was observed in CT treatment at the post-tillage and flowering stages. FA on soils with clay texture significantly increased ($p < 0.05$) *VWC* (Figs. 8d–f). Generally, the post-tillage, flowering, and post-harvest stages of CF treatment had the highest increases in *VWC* (*VWC* of 0.58, 0.31, and 0.31 $cm^3 cm^{-3}$, respectively).

The statistical description of *VWC* data is presented in Tables 2 and 3, illustrating the *VWC* results for different

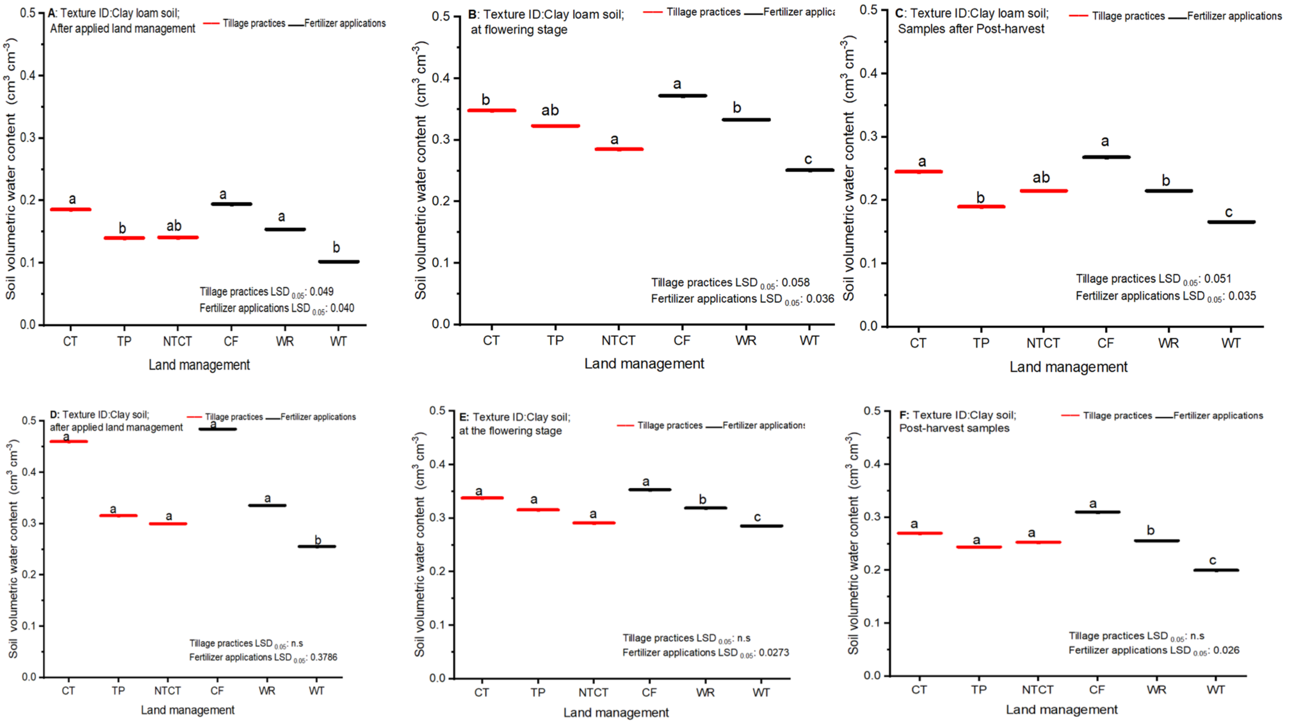


Fig. 8 Mean and context of the analysis of variance of the mean soil volumetric water content for the clay loam/clay soil during the post-tillage, flowering, and post-harvest stages with different agronomic practices. CT: conventional tillage by Moldboard plow + single pass of rotary harrowing; TP: Till-plant using a wheat seed fertilizer drill machine; NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing; CF: cattle manure; WR: wheat straw; WT: without added fertilizer. The same letters above the histograms indicate no significant difference at $p > 0.05$, while different letters indicate significant differences at the 0.05 level. The line in the figures shows the mean (mean: $n = 9$)

land management treatments on two soil textures during different wheat growth stages. The assessment of soil water content and *ρb* during the whole lifecycle of wheat growth is required to calculate *VWC*. *VWC* estimates for the clay loam experimental site were 0.15, 0.31, and 0.22 $m^3\ m^{-3}$ for the post-tillage, flowering, and post-harvest stages, respectively (Table 3). In the clay soil experiment, *VWC* was estimated to be 0.31, 0.31, and 0.25 $cm^3\ cm^{-3}$ for the post-tillage, flowering, and post-harvest stages, respectively. Tillage practices with FA were found to significantly affect the *VWC* estimated for both experiments. Overall, *VWC* decreased by 5.4% in the post-tillage and flowering stages when compared to the post-harvest stage.

The mean *VWC* estimated throughout the wheat growing period for both experiments using coefficients of variation (CV) resulted in a distribution of 9.1 to 21% for clay loam and 5.1 to 9.9% for clay texture soil. Our study also demonstrated that the coefficient of determination (R^2) for *VWC* (dependent variable) was influenced by tillage practices with FA treatments as independent variables (CT, TP, NTCT, CF, WR, and WT) for clay loam at the tillage stage, which accounted for 77% of the variability of *VWC* ($R^2 = 0.77$, $p < 0{,}05$). On the other hand, the R^2 of *VWC* values increased by 0.85% and 0.87% during the flowering and post-harvest stages, respectively (Table 2). A regression analysis was also performed for the three wheat growing stages at the second experimental site (Table 3). The relationship between *VWC* and land management accounted for 89% of the variability seen at the post-tillage stage ($R^2 = 0.89$, $p < 0.05$), 88% of the variability at the flowering stage ($R^2 = 0.88$, $p < 0.05$), and 85% at the post-harvest stage ($R^2 = 0.85\%$, $p < 0.05$), only 7% higher than that of the previous site.

3.4 Soil bulk density (*ρb*)

Soil *ρb* was measured during the post-tillage, flowering, and post-harvest stages under different land management treatments for the two sites, as shown in Fig. 9 and Tables 2 and 3. In the clay loam soil, *ρb* values ranked TP > CT > NTCT at the post-tillage stage, with significant differences ($p < 0.05$) only found between CT and TP, and between TP and NTCT, which was analogous to the flowering and post-harvest stages (Figs. 9 b-c).NTCT treatment was applied as two years of no-tillage and one year of conventional tillage using a disc plow with a single pass of RH. While NTCT showed lower *ρb* during the wheat growing

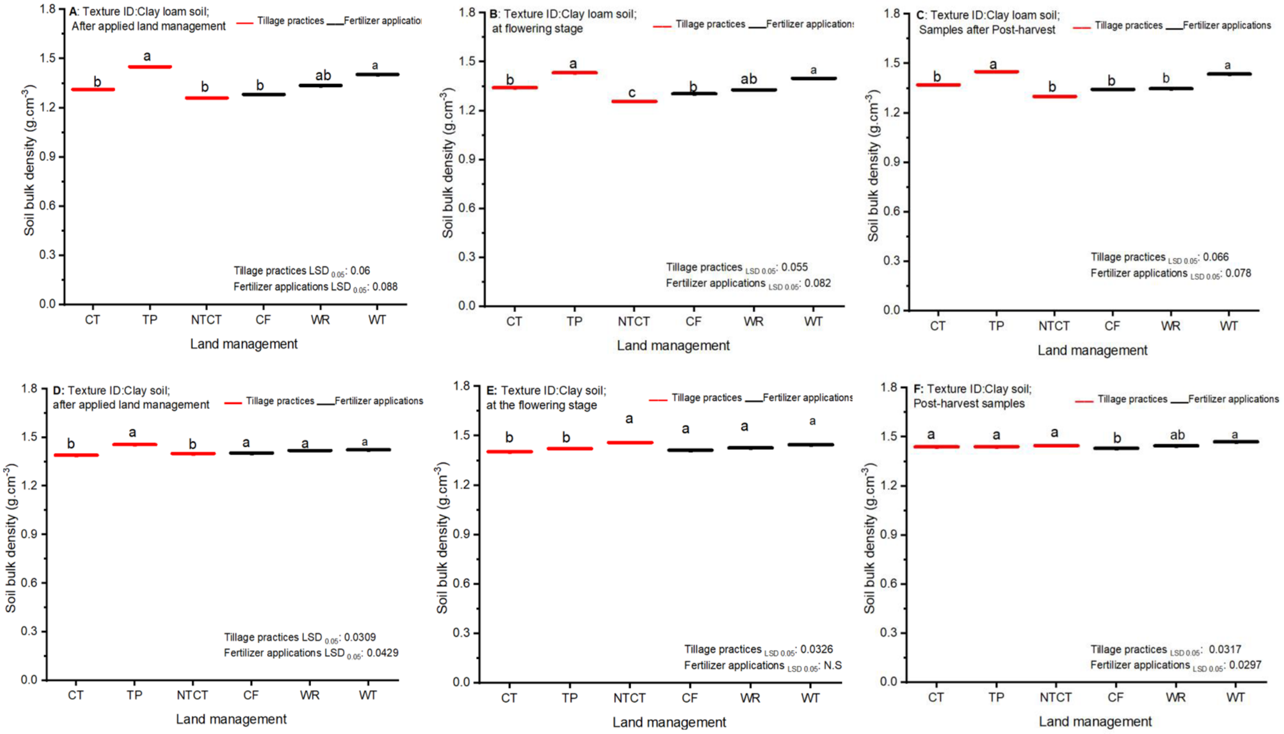


Fig. 9 Mean soil *ρb* (bulk density) of clay loam/clay soil under the influence of land management techniques at post-tillage, flowering, and post-harvest stages. CT: conventional tillage by Moldboard plow + single pass of rotary harrowing; TP: Till-plant using a wheat seed fertilizer drill machine; NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing; CF: cattle manure; WR: wheat straw; WT: without added fertilizer. The same letters above the histograms indicate no significant difference at $p > 0.05$, while different letters indicate significant differences at the 0.05 level. The line in the figures shows the mean (mean: $n = 9$)

stage, it presented an increasing trend compared to TP and CT. Moreover, NTCT showed no significant differences in *ρb* after 2 years of no-tillage, due to the reduced soil disturbance. These findings are in agreement with the findings of (Topa et al. 2021), which reported significantly higher *ρb* values in no-tillage system treatments when compared to CT. However, with all tillage practice treatments, *ρb* values increased over time as the soil was progressively stabilized under the effects of rainfall, particle resettlement, and cycles of wetting and drying. This is in contrast to Blanco-Canqui and Ruis (2018)who found a reduction in *ρb* values after a long-term no-tillage system led to residue retention.

The variation of *ρb* under CF was statistically significant (p < 0.05) at the post-tillage, flowering, and post-harvest stages in the clay loam field experiment. The lowest *ρb* (1.28 g cm^{-3}) was obtained at post-tillage with CF treatment (Fig. 9a), and WR application did not influence *ρb* across the three soil sample stages (Fig. 9a–c). However, WR treatments generated lower *ρb* values when compared to WT (control). The influence of CF showed a similar increase across the three sample stages, while WR treatments resulted in lower *ρb* values at the post-harvest stage than at the flowering stage. These results could be attributable to the addition of CF resulting in a redistribution of soil pores and improvement in soil structure due to the decomposition of organic matter, which caused a reduction in *ρb* values. As confirmed by Dubey et al. (2022), Shakoor et al. (2021), the addition of animal manure can reduce *ρb* values in different soil textures. As for the plant manure represented by WR, the reduction in *ρb* was minor when compared to the reduction seen under CF treatment, possibly because WR contains high levels of lignin, cellulose, and hemicellulose compounds, which are characterized by slow decomposition. These findings could be the result of an increased total soil volume due to the addition of straw material. Other studies (Gunina & Kuzyakov 2014; Laird & Chang 2013; Yang et al. 2016) have reported that plant manure can increase soil organic matter, consequently improving soil aggregation and structure, and therefore decreasing *ρb*.

In the clay soil experiment, *ρb* values increased in the post-tillage and flowering stages but decreased with soil CT. Soil *ρb* at the post-harvest stage showed no significant differences across the tillage practices used. This can be explained using the same rationale used for the variation in *ρb* found in clay loam soil. This is in agreement with work done by (de Moraes et al. 2016; Seben Junior et al. 2014).

Compared to the initial ρb in the soil experiment (Table 1), the ρb in clay soils after FA showed no significant difference in CF, WR, and WT treatments at the post-tillage or flowering stages (Fig. 9d, e), but a significant difference between CF and WT at the post-harvest stage. The CF and WR treatments slightly reduced soil ρb when compared to WT (control). At both sites, the interactive effect of tillage practices and FA for soil ρb were significant for all three soil sample stages, as shown in Tables 2 and 3.

Regression analysis was performed for the three soil sample stages for both experimental sites, with soil ρb as the independent variable and tillage practices and FA as dependent variables (Tables 2 and 3). For clay loam soil, R^2 was found to be 0.91, 0.89, and 0.85% for the post-tillage, flowering, and post-harvest stages, respectively. In the clay soil, the R^2 of soil ρb values were similar or slightly reduced when compared to the clay loam soil experiment. Furthermore, our study demonstrated that the CV of the land management practices used across the three soil sample stages may have contributed to variations in ρb.

3.5 Mean weight diameter (MWD) of aggregates

Results for the effect of different land management practices on MWD for two soil textures at three soil sample stages are displayed in Fig. 10. In the clay loam soil, after the initial 14 days of post-tillage, tillage practices significantly impacted on the MWD of soil aggregates, and aggregate stability assessed by the MWD was higher in NTCT treatments when compared to TP and CT treatments. Additionally, results showed that the MWD of soil aggregates for the flowering and post-harvest stages were similar. In the clay texture soil, the relationship between soil aggregate stability and tillage practices was also different. TP increased the MWD across all three soil sample stages (i.e., post-tillage, flowering, and post-harvest), while NTCT increased the MWD in the post-harvest stage. Specifically, when compared to CT, NTCT significantly improved the MWD aggregates by 39% in the post-harvest stage. TP and NTCT also significantly increased the MWD by 23% in the flowering stage ($p < 0.05$), probably due to an increase in soil stability caused in NTCT and TP soil treatments. Of note, CT tillage mechanically destroys macro-aggregates, thus reducing the MWD of soil aggregates (Wang et al. 2019). Another possible explanation is that the increase of SOC contents found in NTCT and TP treatments may cause the formation of stabilized macro-aggregates, similar to that which was argued by Hu et al. (Hu et al. 2021). To control the deterioration of the soil's structure, the use of organic fertilizer is necessary. The effect of FA treatment on the MWD across

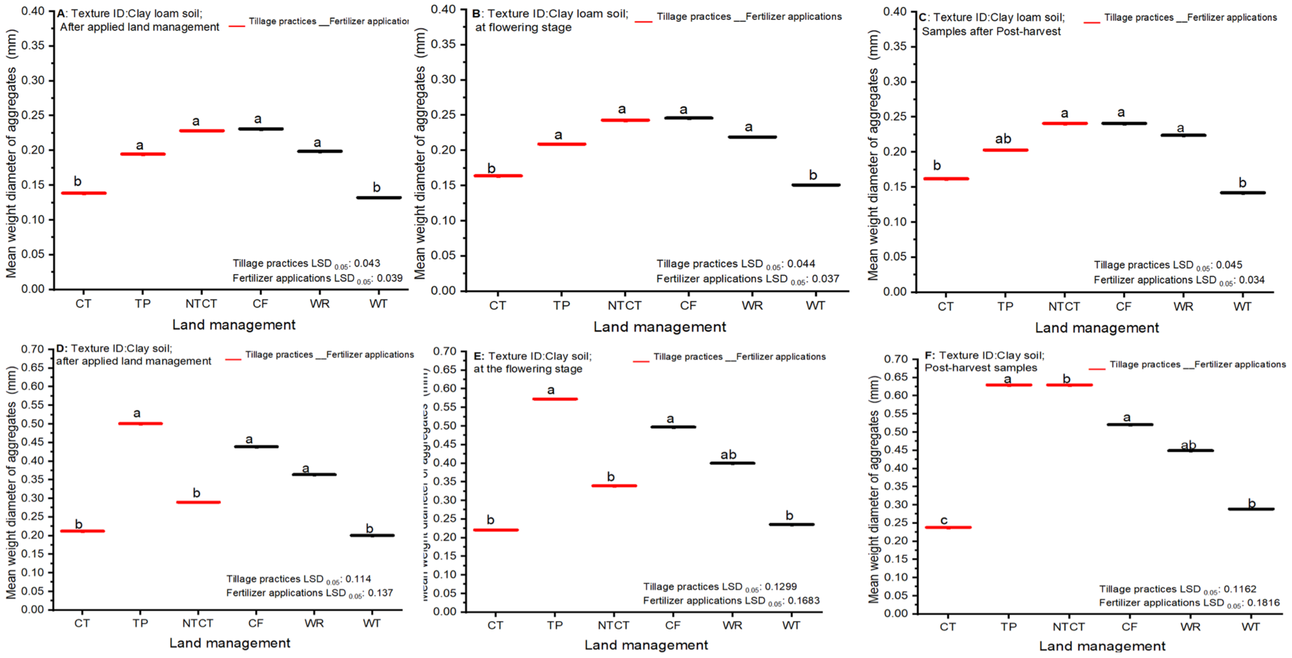


Fig. 10 Mean weight diameter of aggregates of clay loam/clay soil under the influence of land management techniques at post-tillage, flowering, and post-harvest stages. CT: conventional tillage by Moldboard plow + single pass of rotary harrowing; TP: Till-plant using a wheat seed fertilizer drill machine; NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing; CF: cattle manure; WR: wheat straw; WT: without added fertilizer. The same letters above the histograms indicate no significant difference at $p > 0.05$, while different letters indicate significant differences at the 0.05 level. The line in the figures shows the mean (mean: $n = 9$)

the three soil sample stages is also shown in Fig. 10a–f for both sites, though the MWD was not shown to be significantly improved ($p \leq 0.05$) between CF and WR. MWD values were higher with CF treatment for all three soil sample stages. Moreover, a 10% increase in the MWD was found for CF treatments when compared to WT (control) at the tillage and post-harvest stages (Fig. 10a, c). Similarly, with clay soil, FA also significantly improved the soil's MWD in CF and WR treatments when compared to WT (control), as shown in (Fig. 10d–f).

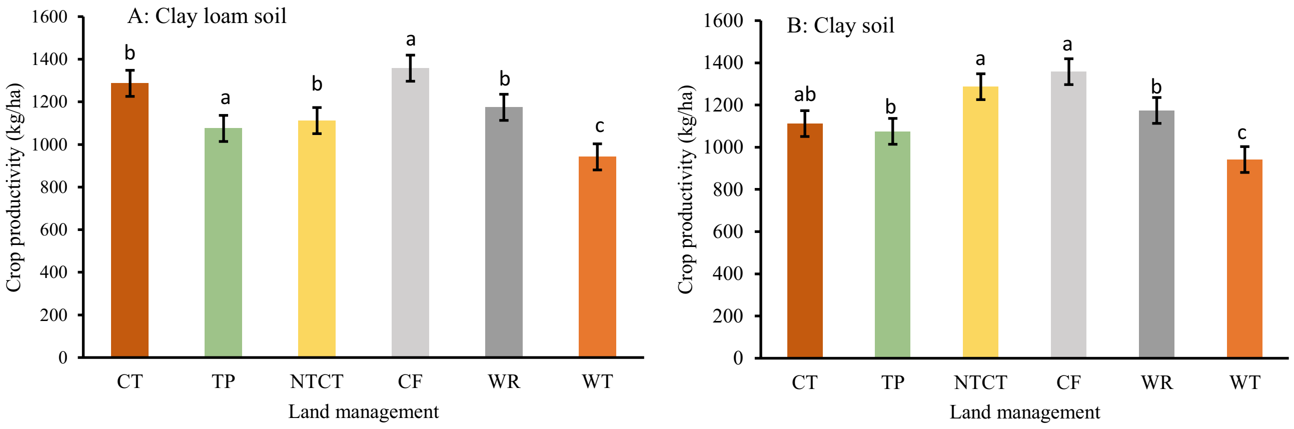
The addition of CF to soil caused a significant increase in SOM, which led to the formation of more stable aggregates as a result of an increased linkage between soil particles. This resulted in a decreased macro-aggregate collapse and increased soil structural stability, similar to results found by Chardravansi et al. (1999), Eltaif et al. (2011), MENG et al. (2016), Meng et al. (2019).

At both experimental sites, the interactive effect of tillage practices and FA for soil MWD showed significant differences in all three soil sample stages (Tables 2 and 3; clay loam, clay). Variance homogeneity (R^2) of the MWD values was also tested, due to the land management parameters studied in both soil textures at the three soil sample stages. In clay loam soil, the proportion of the R^2 at the post-tillage, flowering, and post-harvest stages were 0.98, 0.95, and 0.98%, respectively (Table 2, clay loam). Additionally, for clay soil, this study showed that R^2 values of the MWD were similar to those found for clay loam soil (Table 3). These results showed a CV ranging from 3.9 to 6.55% for clay loam soil and from 7.3 to 11.1% for clay soil (Table 3).

3.6 Wheat productivity (WP, kg ha^{-1})

WP of all land management treatments for both soil textures differed significantly ($p < 0.05$) with tillage practices and FA, as shown in Fig. 11. For clay loam soil, soil treatment by NTCT produced significantly higher WP than did CT and TP by 27% and 19.5%, respectively (Fig. 11a). This was due to NTCT improving the soil's structure (Guo et al. 2017; Obia et al. 2020), in addition to the soil ρb and MWD.

Our findings also note that the use of organic manure has a positive impact on WP: CF treatment resulted in the highest WP, obtaining 1506.6 kg ha^{-1} compared to WR and WT (control), which generated 1245.9 and 941.2 kg ha^{-1}, respectively (Fig. 11a). This is due to CF and WR improving the mechanical and water properties of the soil (Omara et al. 2017), which led to a decrease in SCs and SPR (Cui et al. 2023), increasing the WP. Furthermore, the VWC of soil increased with organic fertilizer treatments, which may be why organic fertilizers significantly improved the WP in our study (Ding et al. 2021). It has been reported that the WP was similar in clay soil and clay loam. NTCT had a higher WP than TP and CT soil treatments, and CF had a higher WP compared to WR and WT. Thus, the use of organic manure (i.e., CF and WR) at appropriate rates can result in increased sustainable soil fertility in winter wheat fields, in combination with the influence of tillage systems and organic manure on WP. This study reveals the need for further experimental investigations. Figure 11a, b shows the regression analysis (R^2) and CV for both experiments. Tukey's test was used to check statistically significant differences in WP for the two wheat fields, and confirmed



Tillage practices LSD $_{0.05}$: 276; R^2:0.3; CV:22.9

Fertilizer applications LSD $_{0.05}$: 214.6; R^2:0.57; CV:17.8

Tillage practices LSD $_{0.05}$: 198.7; R^2:0.21; CV:17.5

Fertilizer applications LSD $_{0.05}$: 124.3; R^2:0.69; CV:10.9

Fig. 11 Wheat productivity under different tillage practices and fertilizer applications, on clay loam soil and clay sites. CT: conventional tillage by Moldboard plow + single pass of rotary harrowing, TP: Till-plant using a wheat seed fertilizer drill machine, NTCT: rotational tillage with two years of no-tillage + one year of conventional tillage using disc plow + single pass of rotary harrowing, CF: cattle manure; WR: wheat straw; WT: without added fertilizer. The same letters above the histograms indicate no significant difference at $p > 0.05$, while different letters indicate significant differences at the 0.05 level. R^2: coefficient of determination; CV: coefficient of variation

Table 4 Tukey's test to check statistically significant differences in wheat productivity for two wheat fields, under different tillage practices and fertilizer applications, with soil treatment replicates

	Factor & comparisons	Tillage practices/ replication	Fertilizer applications// replication	Tillage practices × fertilizer applications//replication
Site ID	Site 1: clay loam soil	$p = 0.0201$ $p = 0.9207$	$p < 0.0001$ $p = 0.8726$	$p < 0.0001$ $p = 0.3201$
	Site 2: clay soil	$p = 0.0837$ $p = 0.8208$	$p < 0.0001$ $p = 0.6077$	$p < 0.0001$ $p = 0.1404$

that all tillage practices and FA treatments were significantly different (Table 4).

3.7 Study limitations

Soil physical attributes were addressed in this study using different soil management practices in arid and semi-arid areas. These results might be applicable to clay loam and clay texture properties. Furthermore, adopting appropriate tillage management technology was shown to control the negative effect of surface crusts, soil structure, and physic-hydraulic status on wheat production. Despite the above limitations, several important suggestions can be made for further research. Firstly, long-term field studies should be conducted on the effects of tillage technologies and soil mulch on the formation of soil SCs in different agriculture soil types. Secondly, further research might explore the formation of SCs on crop sizes and vegetable seeds at several planting depths under different soil management practices. Thirdly, the link between soil physical characteristics and the effect of different tillage and cultivation systems (i.e., with and without cultivation rotation) should be more closely examined. Finally, further data collection is required to determine exactly how soil management practices can enhance yield and energy efficiency, as well as economic efficiency under different tillage practices.

4 Conclusions

This study investigated the effects of different tillage systems and manure applications to treat the formation of surface crusts and to improve soil physical attributes in winter wheat fields with two different soil textures. Results showed that conventional tillage had a strong influence on the formation of soil surface crusts of clay loam and clay soil in terms of penetration resistance and water conservation. In contrast, soil tilled by till-plant technology significantly increased penetration resistance and bulk density of both soil textures, and the mean weight diameter of aggregates increased with clay loam due to the increase in soil stability. Tillage technology by rotational tillage also significantly improved wheat productivity.

Furthermore, adding cattle manure significantly decreased soil physical surface crusts and bulk density because of improvements of soil structure and fertility, which prevented soil aggregates from collapsing, increased microbial respiration, and increased the mean weight diameter of aggregates, thus improving water conservation and wheat productivity. Overall, the present study recommends that the use of rotational tillage system and cattle manure would be of great benefit to the soil physical attributes in agri-wheat fields, especially with clay loam and clay textures in southern central Iraq. Future research is warranted to determine the effect of tillage and organic manure on the agri-ecosystems of soil in a long-term field study in semi-arid drylands.

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Declarations

Conflict of interest The authors declare no conflict of interests.

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