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The Technical Evaluation of Three Different Types of Tillage Combined Machines and compared them with Individual Tillage Machines

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Abstract: The objective of this study was to investigate the effects of a locally manufactured combined tillage machine on the draft force, fuel consumption, field efficiency, power loss, and soil pulverization index. The combined tillage machine accomplished the primary, secondary, and deep tillage in a single pass. The combined tillage machine types were compared to individual tillage machines. The combined tillage machine accomplished the primary, secondary, and deep tillage in a single pass. A randomized complete block (RCBD) experiment was the statistical method used for the investigation with three replicates. The field experiments were conducted in silty loam soil. The combined tillage machines were used in three types. The first configuration (T1) consists of a subsoiler+ chisel plow + disk harrow + roller, the second configuration (T2) consists of a subsoiler + chisel plow, and the third configuration (T3) consists of chisel plow + disc harrow at two operating speeds (1.5 and 3 km.h^{-1}). Individual tillage machines were used in three conventional tillage systems M1, M2, and M3. M1. Conventional tillage systems M1, M2, and M3 perform similar tasks to combined tillage machine types T1, T2, and T3 respectively. The results showed that T3 reduced draft force by 40 and 34.35%, saved fuel by 19.88 and 25.89%, and reduced power loss by 54.25 and 37.22%, while increasing field efficiency by 13.64 and 5.63 and the soil pulverization index by 26.67 and 66.24% compared with T1 and T2 respectively. The combined tillage machinesT1, T2, and T3 reduced the draft force and power loss while increasing the field efficiency by 19.05, 22.41, and 53.49%, respectively, compared with conventional tillage systems M1, M2, and M3. The combined tillage machinesT1, T2, and T3 achieved the lowest values of the soil pulverization index, with values of 19.91, 41.93, and 33.10 mm, and saved fuel by 58.68, 41.61, and 26.86% respectively, compared with conventional tillage systems M1, M2, and M3. The results also revealed that operating speed and its interaction with the combined tillage machine types had a significant effect on all of the studied characteristics ($p<0.05$).

Keywords: Combined tillage machine, Draft force, Fuel consumption, Field efficiency, Soil pulverization Index.

Introduction

Developing and improving tillage machines plays a significant role in farming now that agriculture has become a trade rather than a way of life. The main key to success in the agriculture business is efficient management (Zhao *et al.*, 2021). Utilizing a combined tillage machine and decreasing the number of passes is gaining popularity due to its good impacts on time, efficiency, and costs. Tillage machines are often designed to reduce the draft force and energy requirements (Balsari *et al.*, 2021). Consequently, the development of tillage machines able to conduct primary and secondary plowing in a single pass will be highly useful due to the decreased cost of operations of seedbed preparation (Noor *et al.*, 2020).

Energy saving could be by choosing suitable tillage machines of tractor size and operation parameters to the tillage machines (Ranjbarian *et al.*, 2017). One of the most efficient ways of decreasing operations in the field is to utilize combined machines. Many studies show the operations and development of these machines in regards to conducting further operations by the one pass (Taha & Taha, 2019; Usaborisut *et al.*, 2020; Salar *et al.* 2021).

The results of utilizing combined machines led to decreased consumption of energy and field operations cost, an increment the agriculture production in area unit, as well as improving properties of the soil (Prem *et al.*, 2016). Fuel consumption is a critical indication of agricultural equipment performance. Mileusnic *et al.* (2010) found that the use of combined machines reduces fuel consumption by 0.25 to 0.33 $L.ha^{-1}$. Reduced fuel consumption in operations is a sophisticated and a multifaceted operation in which farm management plays a critical role. (Safa *et al.*, 2010).

Fuel consumption is affected by plowing depth, plowing speed, and soil conditions such as soil moisture content, bulk density, and soil texture. Moitzi *et al.* (2014) found that fuel consumption (liter per hectare) decreased with the increasing operating speed by 23.65%. Himoud (2018) found that fuel consumption increased by 73% when speed increased from 1.9 to 4.33 km h^{-1}. Also, increasing wheel slippage leads to increased fuel consumption and reduced field efficiency (Almaliki *et al.*, 2021). Singh *et al.* (2018) found that plowing speed increasing from 1.5 to 4.5 $km.h^{-1}$ led to increasing the wheel slippage ratio from 15.1 to 23.25%.

Productivity may be boosted by combining several processes to prepare the soil for cultivation in a single pass. Dahab *et al.* (2021) confirmed that actual field capacity for combined equipment gave the highest value of actual field capacity compared to the conventional method by the percentage of 61%. Prem *et al.* (2016) revealed that combined tillage machines had higher efficiency, higher the tillage performance index, and provision about 50% from cost and 50.55% of time compared to conventional tillage machines.

Conducting primary and secondary tillage operations often creates a hard soil layer due to increasing passes on the field (Mileusnic *et al.*, 2022), which negatively affects soil properties, time, and costs of operation considerably (Martins *et al.*, 2021). To overcome this problem, it could be used by the combined tillage machines. This combined tillage machine was used to reduce the passes on the field, by carrying out three tillage operations, which are shallow tillage by chisel plow, harrowing by disk harrow and roller, and deep plowing by subsoiler. Therefore, this study aimed to investigate the performance of the three types of combined tillage machines, compared with a sole, similarly configured for each the configuration of combined tillage machine, at various forward speeds under actual field circumstances. In terms of its effect on fuel consumption, draft force power losses by slippage, field efficiency, and soil pulverization index.

Materials & Methods

Description of the combined tillage machine

A combined tillage machine was manufactured to perform primary and secondary tillage operations in one pass for seedbed preparation. The combined tillage machine contained a subsoiler, chisel plow, disk harrow, and roller with a set of hinged links, as illustrated in Figs. 1, 2, and 3. Three parts make up the combination tillage machine. The chisel plow and subsoiler tines make up the first section (Figs. 2, 3, and 4). The chisel plow consists of five shanks arranged in two rows (Fig. 3 parts 8 and 9). On a frame with dimensions of 170 × 120 cm (Figs. 1 and 4). The front row includes three shanks. The subsoiler shank (Fig. 3 parts 10) were fixed behind the rear row of the chisel plow. The shanks were fixed on the frame at an angle of 60^{o} (rake angle) to facilitate the chisel plow penetration of the soil during the tillage operation. The second part includes a frame of disk harrow (Figs. 2 part 4 and 3 parts 4) made of high steel, carbon (angled iron). The tandem disk harrow is fixed to a frame with dimensions of 170 × 120 cm. The tandem disk harrow consists of two groups, and each group includes seven disks (Fig. 5). The distance between disks in the same group is 18 cm. The frame of the tandem disk harrow was a hinged linkage with the frame of the chisel plow and subsoiler tine, and this made the frame of the tandem disk harrow move freely (Figs. 2 part 7 and 3 part 11). The third part includes the frame of the roller (Figs. 2 part 1 and 3 part 1) and roller (Fig. 6). The frame of the roller is made of rectangular hollow iron. The dimensions of the roller frame are 87 × 152 cm. The roller has a corrugated shape to increase the pulverization of the soil. The roller dimensions are 25 and 150 cm in diameter and length, respectively, and its weight is 190 kg. The roller frame featured a hinged linkage with the tandem disk harrow frame, allowing the roller frame to move freely on the soil surface. (Figs. 2 parts 3 and 3 parts 3). All parts of the combined tillage machine work as a single unit. Furthermore, the combined tillage machine could be used in a variety of configurations, such as chisel plow + subsoiler, chisel plows + subsoiler + disk harrow, chisel plow + disk harrow, and chisel plow + disk harrow + roller.

Test of experiment

In this investigation the effect of three different combined tillage machine configurations was studied on field performance parameters. These three configurations of combined tillage machines were:

(i) The combined tillage machine (T1) consisted of a chisel, subsoiler, disk harrow, and roller. They worked at a depth of 20, 60, 10, and 5 cm, respectively.
(ii) The combined tillage machine (T2) consisted of a chisel, and subsoiler. They worked at a depth of 20, and 60 cm, respectively.
(iii) The combined tillage machine (T3) consisted of a chisel and disk harrow. They worked at a depth of 20, and 10 cm, respectively.

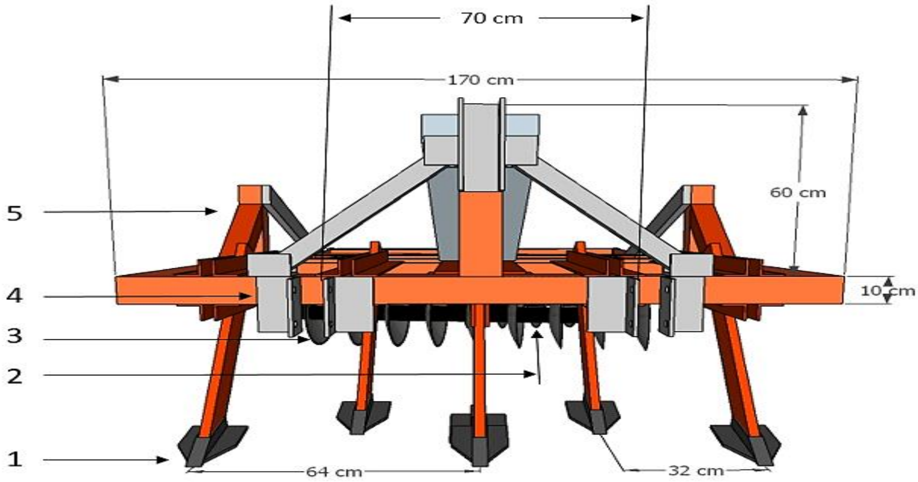
To compare the configurations of combined tillage machines and individual tillage machines. The following tillage equipment was used in three different conventional tillage systems:

(i) The conventional tillage system (M1) consists of four passes. The first pass was done with a subsoiler followed by a second pass with a chisel plow, a third pass with a disk harrow, and the fourth pass with a roller.
(ii) The conventional tillage system (M2) consists of two passes. The first pass was done

with a subsoiler followed by a second pass with a chisel plow.

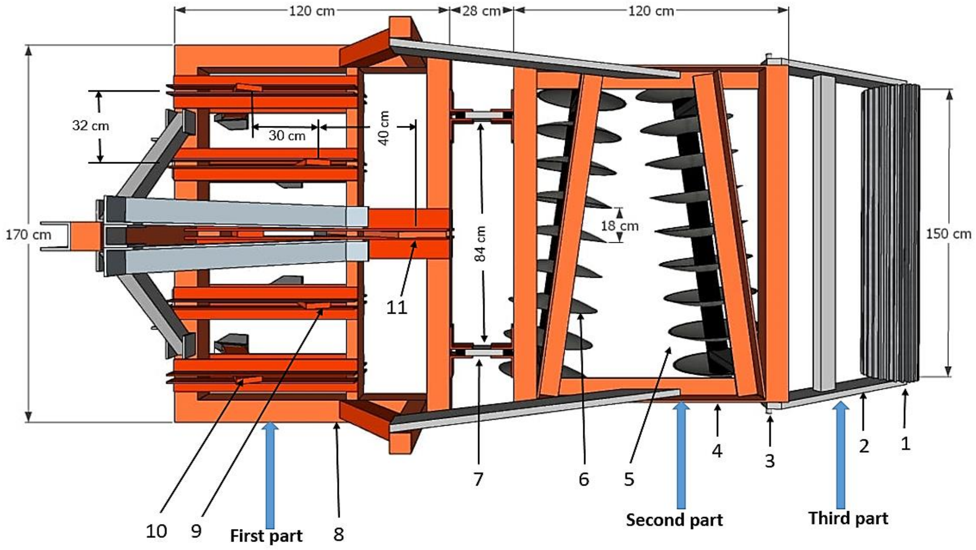
(iii) The conventional tillage system (M3) consists of two passes. The first pass was done with a chisel plow followed by a second pass with a disk harrow.

The tillage depth of the subsoiler, chisel plow, disk harrow, and roller were 60, 20, 10, and 5 cm respectively. Two-level operations speed (1.5 and 3 $km.h^{-1}$) was used when carrying out the tillage operations of the combined tillage machines and individual tillage machines.



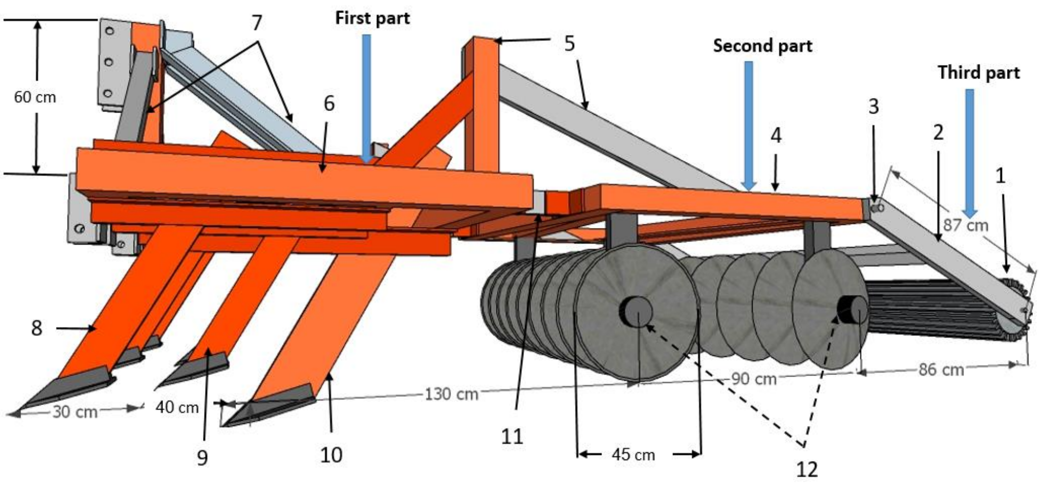
1-Duck foot 2- Roller 3- Disk harrow 4- Lower hitching point 5-Support beams of the hinge part of the disc.

Fig. (1): 3D front view of combined tillage machine.



1- Roller 2- Roller frame 3-The articulation between the two frames of the roller and disc harrow 4- Frame of disk harrow 5- Rear disk gang 6- Front disk gang 7-The articulation between the two frames of the disk harrow and chisel plow 8- Frame of chisel and subsoiler plow 9- Chisel tines in the rear row 10- Chisel tines in the front row 11- subsoiler tine.

Fig. (2): 3D of combined tillage machine.



1- Roller 2- Roller frame 3-The articulation between the two frames of the roller and disc harrow 4- Frame of disk harrow 5- Support beams of the hinge part of the disc 6- Frame of chisel plow and subsoiler 7- Fixation beams of upper point hitching 8- Chisel tines in the front row 9- Chisel tines in the rear row 10- subsoiler tine 11-The articulation between the two frames of the disk harrow and chisel plow 12- disk harrow.

Fig. (3): 3D side view of combined tillage machine.

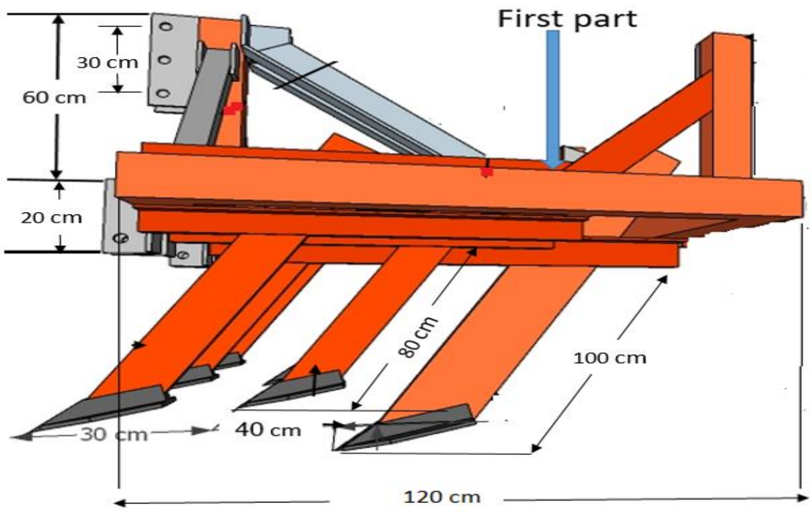


Fig. (4): Chisel and subsoiler plow (First part).

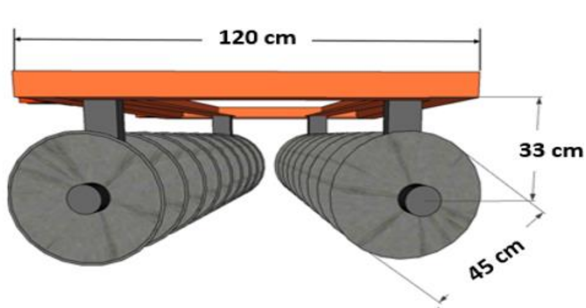


Fig. (5): Disk harrow (Second part).

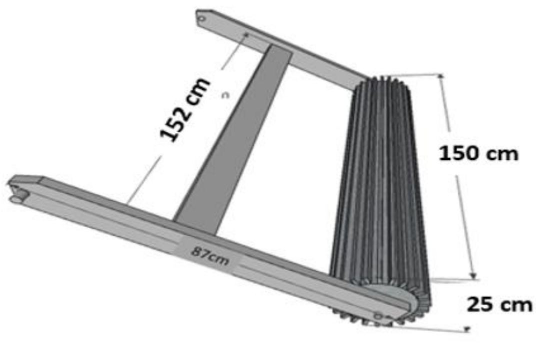


Fig. (6): Roller (Third part).

Fig. (7): Combined tillage machine.

Field measurements

Field efficiency

It is the ratio between actual field capacity and theoretical field capacity. Field efficiency is affected by time wasted in the field such as time spent in turning etc. and failure to use the full width of the machine. The field efficiency was calculated by the following equation (1) according to Prem *et al*. (2017).

Actual field capacity is determined as follows:

$$EFC = \frac{A}{(T_P + T_D)} * 10^{-4} \qquad (1)$$

Where, EFC: effective field capacity (ha.h^{-1}), A: the area of test plot in m^2, T_P is the productive time (h) T_D is the wastage time which includes time of turning, adjustment, and cleaning clogged tools during tillage operation (h).

Theoretical field capacity is determined as follows:

$$TFC = W_E * V * 10^{-1} \qquad (2)$$

W_E is the average effective operating width measured in the field (m), V is the average operating speed (km.h^{-1}).

Effective field capacity: The time wasted in every event such as modification, turning, and the change of gear was registered and time wasted for actual work was utilized. The effective field capacity was calculated by utilizing the following equation:

$$EFC = \frac{A}{T_P + T_t} \qquad (3)$$

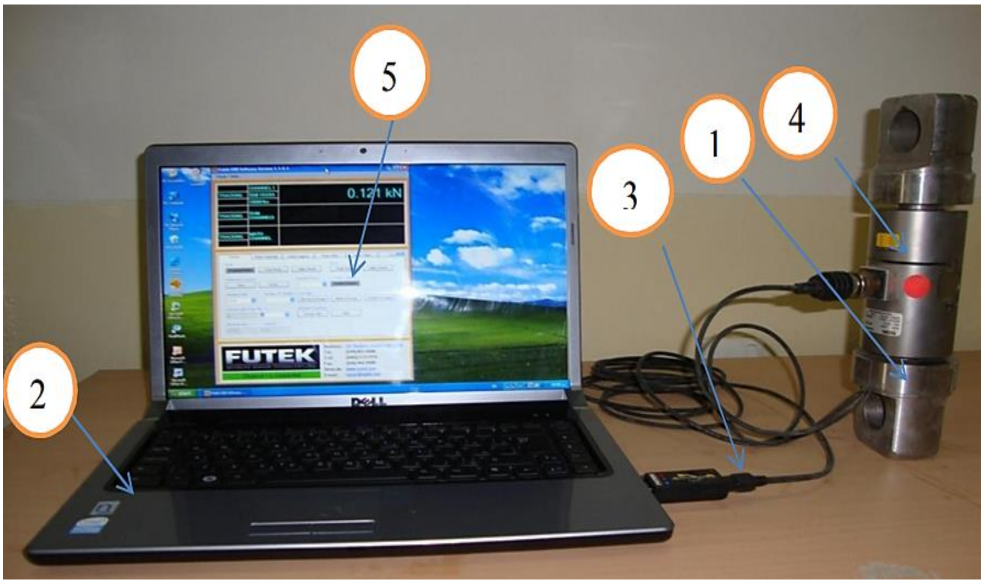
Where, EFC = effective field capacity (ha.h^{-1}); A: Area tilled, ha; Tp: productive time (h); Tt: non- productive time (h).

$$FE = \frac{AFC}{TFC} * 100 \qquad (4)$$

Where: FE: Field efficiency (%), AFC: Actual field capacity (ha.h^{-1}), TFC: Theoretical field capacity (ha. h^{-1})

Draft force measurement

The load cell (Fig. 8) was used to estimate the draft force of the tillage machines. The load cell type, Cylindrical S-Beam and its brand of LSB 600 was made by Futek Advanced Sensor Technology in the USA. The load cell was connected between the main tractor (Massey-Ferguson 440 axtra) and the driven tractor (Massey-Ferguson 285s), which carried the plow. The driven tractor gearbox is set at a neutral position when working. The gearbox of the main tractor (Massey-Ferguson 440 extra) was set in two different positions. The first and second gearbox position was used to execute the low and high operating speed respectively. The engine speed is fixed at 1500 rpm (Almaliki *et al*., 2016). The tractor moves at least 5 m to approach the specific operating speed. The main tractor tows the tractor-plow combination and moves to cover a distance of 30 meters. Every five seconds, the laptop computer connected to a load cell through a USB port recorded the draft force readings for all of the tillage operations under study. Each run was replicated three times.



1- Load cell 2- Lap top 3- USB and connection cable of data 4-linkage points 5- Software recorded and saved data of draft force.

Fig. (8): Draft force measurement device.

Fuel consumption

The fuel tank of the tractor was filled to capacity at the beginning of each run of the tillage practice experiments. The quantity of diesel fuel consumed by the tractor for the tillage practice was estimated at the end of each run by measuring the amount of fuel (Q) needed to refill the fuel tank of the tractor to capacity utilizing measuring a glass tube. The fuel consumption was calculated for this study based on the fuel consumption per unit area plowed ($L.ha^{-1}$). Three replicated were taken for each tillage treatment by using the equation (5) according to Osma *et al.* (2018).

$$FC = \frac{Qd * 10000}{A} \qquad (5)$$

Where: FC: Fuel consumption ($L.ha^{-1}$), Qd: Fuel consumed volume (L), A: Area of Plot = 150 m^2.

Power loss by slippage

Power loss is part of the effective power of the tractor. It was calculated from equation (6) (Md-Tahir *et al.*, 2021)

$$\mathrm{PL} = \mathrm{Pd} - \mathrm{PF} \qquad (6)$$

Where: PL: power loss (kW), Pd: power at driving wheels (kW), PF: Drawbar pull power (kW).

Calculate the Drawbar pull power from the following equation:

$$\mathrm{PF} = \mathrm{F} \times \mathrm{Va} \qquad (7)$$

Where: F: Draft force (kN)

Va: Actual speed ($m.sec^{-1}$)

Calculate the power at driving wheels from the following equation:

$$Pd = H \times V_t \quad (8)$$

Where: H: Thrust (kN), V_t: Theoretical speed ($m.sec^{-1}$)

The Thrust was calculated as follows

$$H = F + R \quad (9)$$

Where: R: Rolling resistance (kN)

Soil pulverization index (dry mean weight diameter)

After tillage by a combined tillage machine and independent tillage machines, blocks of soil were left on the field surface to dry in the air for six weeks, then the soil blocks were collected. The soil sample was taken to the laboratory, weighted and passed through set sieves of 120, 100, 75, 35, 20, 10, 5, and 2 mm. Pulverization index (PI) was estimated from the equation (10) (Nassir, 2018).

$$Spi = \frac{\sum Wi * d}{W_{total}} \quad (10)$$

Where: Spi: Pulverization index (mm), Wi: The mass of the soil obtained between two sieves (kg), W_{total}: Weight of the total mass (kg), d: Average sieve size (mm).

Initial soil properties

Soil samples were taken before conducting the experiments to evaluate the soil, water content and bulk density of soil (Black *et al.*, 1965). The soil penetration resistance, adhesion, and cohesion forces were estimated for depths from 20 to 60 cm (Zheng *et al.*, 2021). The results of soil analysis and soil texture were summarized in table (1).

Table (1): Initial soil properties of field study.

Plowing depth (cm)	Moisture content (%)	Bulk density ($Mg.m^{-3}$)	Soil penetration ($kN.m^{-2}$)	Cohesion ($kN.m^{-2}$)
0-20	10.55	1.23	1820	13.04
20-40	19.19	1.31	1960	16.27
40-60	25.48	1.45	2270	20.12
Average	18.41	1.33	2016.67	16.48
Soil texture (Silty loam)	Clay	($g.kg^{-1}$)	230.87	
	Silt		547.73	
	Sand		220.67	

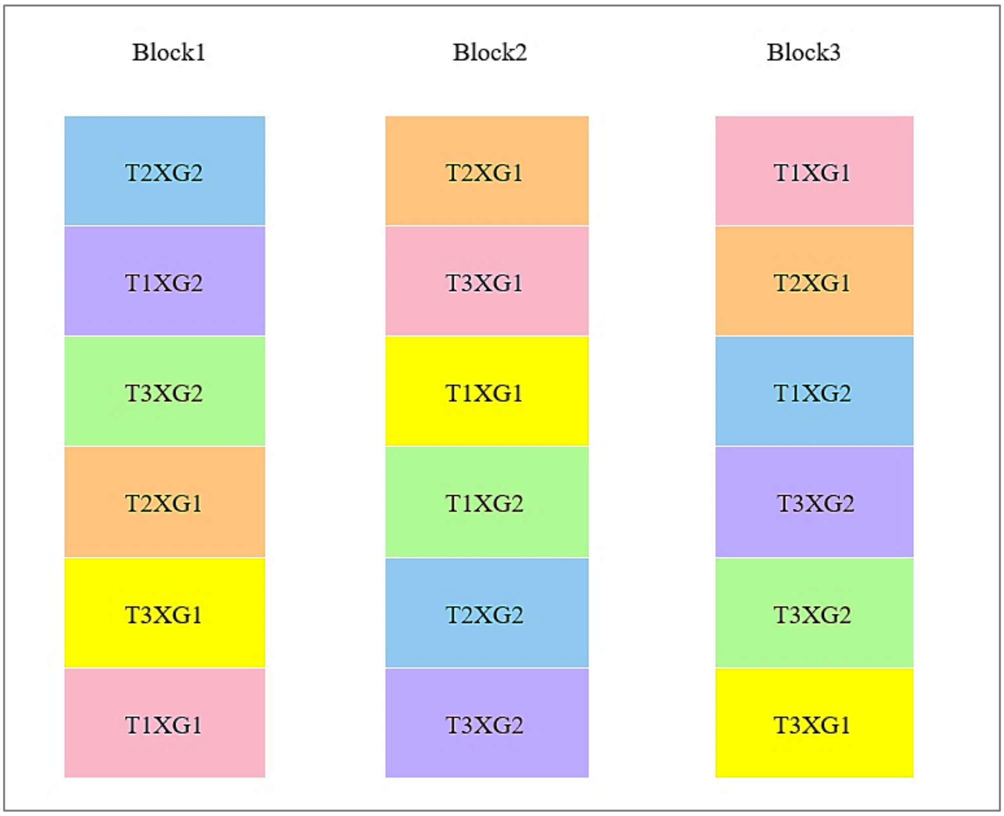
Statistical analysis

Statistical analysis was accomplished by SPSS software (version 9.0). Analysis of variance (ANOVA) was used to evaluate the significance of three combined tillage machine configurations (T1, T2, and T3) and two levels of operation speeds (1.5 and 3 $km.h^{-1}$), on studying parameters. Experiments were carried out with three replications. The experimental area was divided into three blocks (Fig. 9). Each block was divided into six plots. The number of experimental units is 18. The unit dimensions are 20×5 cm. Tillage treatments were spread on experimental units randomly.

A plot of around 3 m long was utilized as a practice area prior to the start of the test runs to allow the tractor and the machine to reach the needed operating speed and tillage depth. The least significant difference (LSD) test was performed to compare differences the least significant difference (LSD) test was performed to compare differences in means of the parameters at significance, level of $P \leq 0.05$. The LSD was calculated from the following equation: Lohr (2021).

$$LSD_{1,2} = t_{0.05,df}\sqrt{\frac{2Mse}{r}} \qquad (11)$$

Where: $t_{0.05,\ DFw}$: The t-critical value from the t-distribution table with α = .05 and df is the degrees of freedom for experimental error from the ANOVA table. Mse: Mean squared error from the ANOVA table. r: The replications number for each treatment.



T1, T2, and T3 are combined tillage machine types. G1 and G2 are operation speed of 1.5 and 3 $km.h^{-1}$ respectively.

Fig. (9): Layout of field experiment.

Results & Discussion

Field efficiency

Table (2) represents the effect of combined tillage machine type and operation speed in field efficiency. Statistical analysis showed that there were significant differences ($P<0.05$) between combined tillage machine combinations. T3 recorded the maximum field efficiency of 75%, followed by T3 (78.75 %), while the minimum value of field efficiency was recorded by T1 reached 66%. The combined tillage machine (T1) manipulates a considerable volume of soil, and the selfweight of T1 is heavy because of consists of a subsoiler, chisel plow, disk harrow, and roller, and this reduces speed and increases the time required to accomplish the preparation of seedbed, may be reasons to reduce the field efficiency for T1 (Usaborisut & Prasertkan, 2019).

Also, the results showed that the field efficiency, increased significantly ($P<0.05$) with the increasing operation speed. The high operating speed of 3 km.h^{-1} recorded the maximum value of field efficiency of 73% while the lowest operation speed of 1.5 km.h^{-1} recorded the minimum value of field efficiency of 67%. This was because the high operation speed leads to e less time required for seedbed preparation. These results agree with Prem *et al*. (2016), who indicated that increasing operation speed leads to increased field efficiency by reducing tillage, time, where field time is a critical factor that must be assessed when measuring the field efficiency of any tillage machine. The previous work conducted by Muhsin (2017a) showed a similar tendency. He found that when the operation speed increased from 2.54 to 5.77 km.h^{-1}, the mean of field efficiency increased by 10.89%, and mentioned the reason was that increase in the forward speed led to an increase in the actual field capacity, result from the positive relationship between them, where the effective field capacity approached from theoretical field capacity, thereby the field efficiency increased.

Results showed a significant interaction effect ($p<0.5$) between combined tillage machine combinations and speed operation in the field efficiency. The combine tillage machine (T3) and high speed of 3 km.h^{-1} recorded the highest value of the field efficiency of 77%. While the lowest field efficiency value of 63% was registered by the combined tillage machine (T1) and the low speed of 1.5 km.h^{-1}. This was because the design of T3, which consists of a chisel plow and disk harrow only and this makes the combined tillage machine slight weight and works in shallow depth of 20 cm leads to reducing energy requirements and saving time, particularly at high operation speed. This is in line with the finding of Prem *et al.* (2017) who the field efficiency of the cultivator was found to be 6.35 % greater than that of the combination tillage machine. This was due to additional time needed during turning of the combination tillage machine as well as the lower operation speed because of higher slip.

Statistical analysis reveals highly significant differences ($p<0.05$) among combined tillage machines and individual machines (conventional tillage system) in the field efficiency. Table (3) indicates the comparison of field efficiency for the combined machine and the individual tillage machines. It can be observed that the combined tillage machine T1, T2, and T3 registered the values of field efficiency, higher than that of conventional tillage systems M1, M2, and M3 by 53.49, 31.03, and 19.05% respectively. This was because the combined tillage machine in one path performs all tillage operations done by the individual tillage machines (conventional tillage systems) and almost in less time. This is in line with the finding of Dahab *et al*. (2021). They reported a field efficiency, increased by 55% compared with individual tillage machines (conventional tillage systems). The previous work carried out by Osma *et al.* (2014) showed a similar trend. They indicate that the field efficiency for conventional plow was lower than that for modified plow and the difference between the values of field efficiency was reduced by 14.58% due to the modified plow reducing the time required for plowing soil considerably.

Table (2): Effect of combined tillage machine and speed in field efficiency (%).

Operating speed (km.h^{-1})	Combined tillage			
	T1	**T2**	**T3**	**Mean**
1.5	63 ± 1.3	68 ± 1	71 ± 1.5	67 ± 1.9
3	69 ± 1.7	74 ± 2	77 ± 1	73 ± 1.56
Mean	66 ± 1.5	71 ± 1.5	75 ± 1.25	
L.D.S.$_{(0.05)}$	Tillage type (1.403), speed (0.887), Tillage type × speed (1.897)			

The combined tillage machine (single pass), (T1) consist of a chisel + subsoiler + disk harrow + roller, (T2) consist of a chisel + subsoiler, (T3) consist of a chisel + disk harrow.

Table (3): Total field efficiency (%) for conventional tillage and combined tillage machines.

Combined tillage			Conventional tillage		
T1	**T2**	**T3**	**M1**	**M2**	**M3**
66 ± 1.7	71 ± 2.3	75 ± 1.1	43 ± 1.11	58 ± 1.5	63 ± 1.86
LSD$_{(0.05)}$				**2.47**	

The combined tillage machine (single pass): (T1) consist of a chisel + subsoiler + disk harrow + roller, (T2) consist of a chisel + subsoiler, (T3) consist of a chisel + disk harrow.
The conventional tillage systems: (M1) consists of four passes. The first pass was done with a subsoiler followed by a second pass with a chisel plow, a third pass with a disk harrow, and the fourth pass with a roller, (M2) consists of two passes. The first pass was done with a subsoiler followed by a second pass with a chisel plow, (M3) consists of two passes. The first pass was done with a chisel plow followed by a second pass with a disk harrow.

Draft force

The results revealed that significant differences (P<0.05) were observed among combined tillage machine combinations (table 4). The highest draft force of 32.39kN was obtained by T1. In contrast, T3 obtained the lowest draft force (19.43kN). However, T2 obtained the medium draft force value of 29.60 kN. This was due to the difference between tillage machine combinations in terms of geometric design, where T1 was heavy because it consists of a subsoiler, chisel plow, disk harrow, and roller, as well as T1, working on considerable depth and breaking down a large volume of soil leading to increased draft requirements compared with T2 and T3. This is in line with the finding of Ranjbarian *et al.* (2017) who found the draft requirements of the combined plow were reduced by 11.3% compared to the use of a heavy chisel plow due to reducing the energy required to pull the combined plow. The results showed a significant increase in the draft force in all the treatments with an increase in operation speed (p<0.05) (table 4).

Increasing operation speed from 1.5 to 3 km.h^{-1} increased the draft force from 25.41 to 28.87 kN. This was mainly attributed to the acceleration of the soil clods and accumulated it in front of plow shanks leading to an increase in the draft requirements (Nassir *et al.,* 2016) who found when the forward speed was increased from 2.3 to 4.6 km.h^{-1}, the drag force increased by 29.41% and the reason was the acceleration of the soil. Greater forces provide this acceleration and, a higher sliding resistance result. The increased sliding resistance contributes most of the increased draft force.

The results also showed that there was a significant effect of the interaction between the combined tillage machine combinations and operation speed (p<0.05) (table 4). The high operating speed of 3 km h^{-1} and plowing by T1, T2, and T3 obtained the highest values of the draft force in 34.39, 30.66, and 21.55 kN respectively. While the values of the draft force for T1, T2, and T3 decreased by 11.66, 6.91, and 19.68% respectively at a reducing operating speed of 1.5 $km.h^{-1}$. This was because of the higher soil resistance and more volume of soil handled with an increase in depth at plowing by T1 and higher draft requirements to the acceleration of soil blocks with an increase in speed of operation. This is in accordance with Ramadhan (2014).

The results showed that there were significant differences ($P<0.05$) among combined tillage machines and individual machines (conventional tillage system) in the draft force (Table 5). The result showed that combined tillage machinesT1, T2, and T3 decreased the draft force by 31.72, 20.94, and 14.57% compared with the conventional tillage systems M1, M2, and M3 respectively. The soil was tilled in one pass using the combined tillage machines. A subsoiler was used for plowing the deep layer of soil to a depth of 60 cm, while a chisel plow was used for plowing the surface soil layer to a depth of 20 cm. Because of the interference between the operations of the two plows, the needed draft force to cut and break down was decreased, causing a decreasing power loss. While using individual machines to prepare the soil bed requires additional field passes. Increased field passes compact the soil (Jabro *et al*., 2021), making it more difficult to distribute, and this leads to increased draft requirements and subsequently increasing draft force. Similar results were also reported by Dahab *et al.* (2021) who found that combined tillage machines were reduced the draft force by 23.46% compared to individual machines (conventional tillage system).

Table (4): Effect of combined tillage machine and speed in draft force (kN).

Operating speed ($km.h^{-1}$)	**Combined tillage**			
	T1	**T2**	**T3**	**Mean**
1.5	30.38 ± 0.58	28.54 ± 0.87	17.31 ± 0.91	25.41 ± 0.79
3	34.39 ± 0.57	30.66 ± 0.40	21.55 ± 0.67	28.87 ± 0.55
Mean	32.39 ± 0.56	29.60 ± 0.64	19.43 ± 0.79	
L.D.S.$_{(0.05)}$	Tillage type (0.806) speed (0.36) Tillage type × speed (1.14)			

M1 equivalent T1, M2 equivalent T2, and M3 equivalent T3

Table (5): Total draft force (kN) for conventional tillage and combined tillage machines.

	Subsoiler	Chisel	Disk harrow	Roller	Total
M1	22.17 ± 1	15.27 ± 0.8	6.97 ± 1.3	2.63 ± 1.7	47.04 ± 0.95
M2	22.17 ± 1	15.27 ± 0.8			37.44 ± 0.90
M3		15.27 ± 0.8	6.97 ± 1.3		22.24 ± 1.05
T1					32.39 ± 0.56
T2					29.60 ± 0.64
T3					19.43 ± 0.79
LDS.$_{(0.05)}$					1.48

Fuel consumption

The mean values of fuel consumption in liter per hectare ($L.ha^{-1}$) were summarized in table (6). Results showed that significant differences ($P<0.05$) were indicated between combined tillage machine combinations. The highest value of fuel consumption of 36.13 $L.ha^{-1}$ was obtained by T1, followed by T2, which obtained the second value of fuel consumption of 33.30 $L.ha^{-1}$. In contrast, T3 obtained the lowest value of fuel consumption of 26.68 $L.ha^{-1}$. This was due to the differences between combined tillage machine combinations in terms of geometric design and this affected the energy required for combinations of combined tillage machines, where T1 required more energy than that of T2 and T3 because the T1 is heavy and work at large depth reach to 60 cm consequently the tractor engine needed to much fuel for pull when plowing by T1. These results are also in line with the results reported by Moitzi *et al*. (2014) who found that deep plowing by heavy combined tillage machine increases fuel consumption by 72% compared with plowing by light combined tillage machine, and may be partially explained by the work of Inthiyaz *et al.* (2020) who found the modified disk harrow reduced fuel consumption by 53% compared to the traditional disk harrow. This was because the modified disk harrow reduced energy and draft requirements, thereby saving fuel.

The results illustrated in the table (6) showed that an increase in operating speed from 1.5 to 3 $Km.h^{-1}$, leads to the fuel consumption of the tractor decreasing significantly ($p<0.05$). Increasing operating speed from 1.5 to 3 km h^{-1} decreased the fuel consumption from 34.02 to 30.06 $L.ha^{-1}$ (11.62%). This was attributed to the ineffective utilize of tractor capacity when operating at a relatively low speed, leading to energy loss, while in the case of the high speeds, this energy is better exploited and this decrease the time needed to complete the plowing of the unit area, thereby reducing the fuel consumption at high speed. These results are consistent with the findings of Himoud (2018) who indicated that increasing operating speed from 3.4 to 5.26 $Km.h^{-1}$ resulted in a decreased in fuel consumption by 22.74%.

The results showed a significant interaction effect ($p<0.5$) between combined tillage machine combinations and speed operation in the fuel consumption (table 6). The combined tillage machine (T3) and high speed of 3 $km.h^{-1}$ recorded the lowest value of fuel consumption of 25.28 $L.ha^{-1}$. While the highest fuel consumption value of 28.08 $L.ha^{-1}$ was registered by The combined tillage machine (T1) and the low speed of 1.5 $km.h^{-1}$. This was attributed to the combined tillage machine (T3) operating at a shallow depth of 20 cm, and this resulted in lower energy consumption. On the other hand, a higher operating speed decreased the time required for tillage operations, thereby saving a considerable amount of fuel. This is in accordance with Sven (2019).

Comparing the effects of combination tillage equipment and individual tillage machines on fuel consumption. The results illustrated in table (7) showed that clearly, the combined tillage machine reduces the fuel consumption significantly ($p<0.05$) as compared with the four individual tillage machines. The fuel was saved by 58.68, 41.61, and 26.86% when plowing by T1, T2, and T3 compared to M1, M2, and M3 respectively. This was because the combined tillage machine in one pass accomplishes the four tillage operations done by the individual tillage machines in four passes, and this makes the combined tillage machine save a considerable amount of fuel compared with individual tillage machines, which required more fuel to accomplish the same tillage operations. This agrees with (Dahab *et al.*, 2021) who reported the combined tillage machine saved fuel by 57% compared with individual tillage machines.

Table (6): Effect of combined tillage machine and speed in fuel consumption (L.ha^{-1})

Operating speed (km.h^{-1})	Combined tillage T1	T2	T3	Mean
3	33.46 ± 1.45	31.44 ± 1.38	25.28 ± 0.97	30.06 ± 1.27
1.5	38.81 ± 1.02	35.16 ± 1.20	28.08 ± 1.35	34.02 ± 1.19
Mean	36.13 ± 1.24	33.30 ± 1.29	26.68 ± 1.16	
L.D.S.$_{(0.05)}$	Tillage type (0.77) speed (0.34) Tillage type × speed (1.09)			

Table (7): Total fuel consumption (L.ha^{-1}) for conventional tillage and combined tillage machines

	Subsoiler	Chisel	Disk harrow	Roller	Total
M1	36.75 ± 1.8	20.28 ± 2.03	16.20 ± 1.77	13.26 ± 1.82	86.49 ± 1.86
M2	36.75 ± 1.8	20.28 ± 2.03			57.03 ± 1.91
M3		20.28 ± 2.03	16.20 ± 1.77		36.48 ± 1.40
T1					36.13 ± 1.24
T2					33.30 ± 1.29
T3					26.68 ± 1.16
LDS.$_{(0.05)}$					1.63

M1 equivalent T1, M2 equivalent T2, and M3 equivalent T3

Power loss by slippage

The results revealed that there were significant differences (P<0.05) among combined tillage machine combinations (table 8). The highest power loss of 8.48 kW was gained by T1 followed by T2, which was obtained a power loss value of 6.18 kW. In contrast, T3 gained the lowest power loss reaching 3.88 kW. This was attributed to the high draft force required by T1, where the combined tillage machine (T1) is heavy and loosens a big volume of soil causing increased draft force thereby increasing the power loss for T1 compared with T2 and T3. This is in accordance with the results reported by Osma *et al.* (2018) who indicated the modified chisel plow saved about 23 up to 59% in the power consumption and about 30 up to 58% in the energy requirements compared with the traditional of a chisel plow.

The operating speed had a significant effect on the power loss (p<0.05). Table (8) showed that increasing operating speed from 1.5 to 3 km.h^{-1} led to an increased power loss by 59.12%. This was because the high operating speed increased the acceleration of the soil blocks which increased the collision of these blocks with unplowed soil existing in front of it causing contrary resistance to the plow movement. However, high operating speed made plow shank penetration of the soil difficult, and thus did not provide the plow sufficient time to produce cracks in the soil body, increasing resistance to plow movement in the soil body and thus resulting in increased power loss when operating speed increased. Similar finding was observed by (Almaliki *et al.*, 2021) who indicated that increasing operating speed from 3 to 5.7 km.h^{-1} led to an increase in power losses by 57.65%, and mentioned the power losses increased due to the wheels slip increased considerably due to the increase in thrust generated by the traction wheels to provide additional power to accelerate the tractor and pull the plow.

The results also revealed that the interaction between the combined tillage machine combinations and operating speed had a significant effect (p <0.05) (table 8). The combined tillage types T1, T2, and T3 at the high speed of 3 km.h^{-1} recorded higher power loss values of 10.03, 7.68, and 5.05 kW, respectively, while at the low operating speed of 1.5 km.h^{-1} recorded lower power loss value of 6.93, 4.68, and 2.70 kW respectively. This was due to higher soil resistance and the considerable volume of the soil handled when deep plowing by T1, particularly at a high speed of operation, which required more energy to accelerate and move the clods of the soil, consequently increasing the power loss (Prem *et al.*, 2017), who revealed that was because part of the power available at the traction wheels was consumed to accelerate the tractor and another portion was dissipated in the slippage of the wheels, which increased with the operating speed. Slippage is the main factor in power losses and higher slippage at higher speeds caused lower power losses.

The results showed that there were significant differences (P <0.05) among combined tillage machines and individual tillage machines (conventional tillage system) in the power loss (Table 9). The result showed that combined tillage machinesT1, T2, and T3 decreased the power loss by 19.471, 16.60, and 25.52% compared with the conventional tillage systems M1, M2, and M3, respectively. This was because the combined tillage machines required draft force and energy, lower than individual tillage machines, and this was due to the combined tillage machine accomplishing the plowing operations in one pass, while individual tillage machines do the plowing operations in four passes. The power loss was calculated by collecting values of the power loss for each plow, and the value represented the total power loss in the conventional tillage system. For example, M1 obtained a power loss value of 10.53 kW. This value of power loss was estimated from a collection of the power loss values for individual tillage machines (subsoiler, chisel plow, disk harrow, and roller). In contrast, T1 obtained a lower power loss value of 8.48 kW in one pass. This is in accordance with Prem *et al.* (2016) who indicate that the power losses decreased highly when used the combined tillage machine compared to individual tillage machines.

Table (9): Total power loss (kW) for conventional tillage and combined tillage machines.

	Subsoiler	Chisel	Disk harrow	Roller	Total
M1	4.28 ± 0.5	3.13 ± 0.77	± 0.672.09	0.85 ±1.03	10.53 ± 0.70
M2	4.28 ± 0.5	3.13 ± 0.77			7.41 ± 0.64
M3		3.13 ± 0.77	± 0.672.09		5.22 ± 0.72
T1					8.48 ± 0.39
T2					6.18 ± 0.65
T3					3.88 ± 0.47
L.D.S.$_{(0.05)}$					1.78

M1 equivalent T1, M2 equivalent T2, and M3 equivalent T3

The pulverization of soil Index

The results revealed that there were significant differences (p<0.05) between the various combinations of combined tillage machines (table 10). The lowest soil pulverization index (high soil pulverization) was gained by T1, where the soil pulverization index was reduced for T1 compared with T2 and T3 by 52.52 and 39.85%, respectively. This was because of the difference in combined tillage machine combinations in terms of geometric design, and this affected the ability of the combined tillage machines to pulverize the soil. For example, in the case of T1, the soil is broken down by a subsoiler at a depth of 60 cm, and the large soil blocks produced by the subsoiler will be broken up into small clods of soil by a chisel plow. After that, the soil clods are pulverized into smaller soil pieces by a tandem disk harrow. However, placing a roller behind the tandem disk harrow can assist in increasing the fragmentation of soil. The T1 accomplishes four tillage operations in a single pass, including primary, secondary, and deep tillage, and this makes the T1 increase the pulverization of the soil compared with T2 and T3. This is in accordance with Ranjbarian *et al.* (2017) who found considerable improvement in soil pulverization with the use of the combined tillage machine (chisel plow & disc harrow) compared with the use of disk harrow by 24.30% due to the ability of the combined tillage machine to break the clod formed by the primary and secondary tillage operations.

The operating speed had a significant ($p<0.05$) effect on the soil pulverization index, it decreased as the operating speed increased (table 10). Increasing the operating speed from 1.5 to 3 $km.h^{-1}$, the soil pulverization index decreased from 34.99 to 28.30 mm by 19.12%. The decrease in the soil pulverization index was because of the self-breaking up of the soil blocks during tillage operation. The blocks of soil collide with each other, causing self-fragmentation of the soil thereby, reducing the value of the soil pulverization index. This is in accordance with Muhsin (2017b), who found that the soil pulverization index decreased by 51.70% when the operating speed increased from 3.70 to 7.22 $km.h^{-1}$. He was mentioned that increasing the soil clods' acceleration and moving may cause an increase in the collision of the soil blocks, resulting in the soil blocks breaking up into small pieces, resulting in increased soil pulverization.

The results also showed that there was a significant effect of the interaction between the combined tillage machine combinations and operation speed ($p<0.05$) (table 10). Plowing by T1 of high speed obtained the lowest soil pulverization index value of 17.19 mm. While plowing by T2, at low speed obtained the highest soil pulverization index value of 47.24 mm. The reduction in pulverization index was due to the self-braking up of the soil blocks during the tillage operation. The soil blocks collide with each other, causing self-pulverization in the soil, particularly when plowing by T1. This is in accordance with (Nassir, 2018; Choudhary *et al*., 2021).

The results showed that there were significant differences ($P<0.05$) among combined tillage machines and individual machines (conventional tillage system) in the pulverization index of soil (Table 11). The result showed that combined tillage machinesT1, T2, and T3 decreased the pulverization index of soil by 40.23, 44.57, and 33.07% compared with the conventional tillage systems M1, M2, and M3 respectively. This was because the combined tillage machine in one pass accomplishes the soil tillage operations. Soil loosening by subsoiler, then soil clods were pulverized by a chisel plow, disk harrow, and roller at the same time, thereby forming small soil clods on the field surface and consequently reducing the pulverization index of soil. On the other hand, the individual tillage machines accomplished the soil tillage operations in four passes, and this could lead to the compaction of the soil, thereby increasing the soil resistance to loosening leading to an increase in the pulverization index. This trend accords with (Usaborisut & Prasertkan, 2019) they reported that the combined tillage machine reduces the pulverization index of soil compared with the individual tillage machines by 8.69%. Also Dahab *et al.* (2021) reported similar results by using a combined tillage machine and found that the combined tillage machine increased the soil pulverization by 25.85% compared with two passes by disk harrow.

Table (10): Effect of combined tillage machine and speed in soil pulverization index (mm).

Operating speed ($km.h^{-1}$)	Combined tillage T1	T2	T3	Mean
1.5	22.64 ± 1.13	47.24 ± 1.22	35.09 ± 1.17	34.99 ± 1.17
3	17.19 ± 1.18	36.61 ± 1.16	31.11 ± 1.25	28.30 ± 1.21
Mean	19.91 ± 1.55	41.93 ± 1.19	33.10 ± 1.21	
L.D.S.$_{(0.05)}$	Tillage type (1.59)	speed (1.26)	Tillage type × speed (2.83)	

Table (11): The soil pulverization index (mm) values for conventional tillage and combined tillage machine.

	Subsoiler	Chisel	Disk harrow	Roller	pulverization index
M1	149.58 ± 5	75.65 ± 2.8	49.75± 2.7	33.31± 1.88	33.31 ± 3.22
M2	149.58 ± 5	75.65± 2.8			75.65 ± 4.15
M3		75.65± 2.8	49.75± 2.8		49.75 ± 2.29
T1					19.91 ± 1.55
T2					41.93 ± 1.19
T3					33.10 ± 1.21
L.D.S.$_{(0.05)}$					**1.83**

M1 equivalent T1, M2 equivalent T2, and M3 equivalent T3

Conclusions

The main results of this investigation can be concluded as follows:

1- Using the combined tillage machine T3 compared to using types of the combined tillage machine T1 and T2 resulted in

(i) Increasing the field efficiency and pulverization index by 13.64 and 5.63%, and 52.52 and 39.85%, respectively.
(ii) Reducing the draft force and loss of power by 40 and 34.35% and 54.25 and 37.22%, respectively.
(iii) Saving fuel by 19.88 and 25.89% respectively.
2- Increasing operation speed from 1.5 to 3 $km.h^{-1}$ led to increases in the field efficiency, draft force, power loss, and pulverization index of soil by 67, 13.66, 59.12, and 19.12%, respectively, while fuel consumption decreased by 9.97%. The interaction between the combined tillage machine and operation speed had a significant effect on all parameters studied.

3-Using the combined tillage machinesT1, T2, and T3 compared to using conventional tillage systems M1, M2, and M3 resulted in

(i) Increasing the field efficiency by 53.49, 31.03, and 19.05%, respectively.
(ii) Reducing the draft force by 31.72, 20.94, and 14.57 %, respectively, as well as the power loss by 19, 17, and 26%.
(iii) Saving fuel by 58.68, 41.61, and 26.86% respectively.
4- It is recommended to use the combined tillage machinestypesT1, T2 and T3 at a low operation speed to reduce draft force and save power and energy for plowing operations, as

well as to solve the main problems caused by using individual tillage machines.

Contributions of authors

A.J.N.: Sample collection, Data collection, Write the manuscript.

S.J.M.: Read and revise the manuscript, statistical analysis of the data.

D.R.N.: Read and revise the manuscript.

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Conflicts of interest

The authors declare that they have no conflict of interest.

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التقييم الفني لثلاثة أنواع مختلفة من آلات الحراثة المركبة ومقارنتها بآلآت الحراثة الفردية

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المستخلص: تهدف الدراسة الى معرفة تأثير آلة الحراثة المركبة المصنعة محليًا في قوة السحب، واستهلاك الوقود والكفاءة الحقلية والطاقة المفقودة ودليل تفتيت التربة. انجزت آلة الحراثة المركبة عملية الحراثة الأولية والثانوية والعميقة في مسار واحد في الحقل وتم مقارنة تراكيب الة الحراثة المركبة بآلات الحراثة الفردية. استخدم تصميم القطاعات العشوائية الكاملة (RCBD) في ثلاث مكررات في التجارب. أجريت التجارب الحقلية في تربة غرينيه مزيجه. استخدمت آلات الحراثة المركبة بثلاث تراكيب، التركيب الأول (T1) يتكون من محراث تحت سطح التربة + محراث حفار + مشط قرصي + حاذلة، ويتكون التركيب الثاني (T2) من محراث تحت سطح التربة + محراث حفار، يتكون التركيب الثالث (T3) من المحراث الحفار + المشط القرصي. أجريت التجارب عند سرعتي حراثة (1.5 و3 كم.ساعة$^{-1}$). أنظمة الحراثة التقليدية M1 وM2 وM3 تؤدي نفس عمليات الحراثة التي تقوم بها T1 و T2 و T3 على التوالي. أظهرت النتائج أن T3 قلل من قوة السحب بنسبة 40 و 34.35٪، ووفّر الوقود المستهلك بنسبة 19.88 و 25.89٪ ، وقلل الطاقة المفقودة بنسبة 54.25 و 37.22٪ مع زيادة الكفاءة الحقلية بمقدار 13.64 و 5.63 ، ودليل التفتيت بنسبة 26.67 و 66.24٪. بالمقارنة مع T1 و T2 على التوالي. حققت آلات الحراثة المركبة T1 و T2 و T3 أدنى القيم لدليل تفتيت التربة بلغت 19.91 و 41.93 و 33.10 ملم ووفرت الوقود بنسبة 58.68 و 41.61 و 26.86٪ على التوالي، مقارنة بأنظمة الحراثة التقليدية M1 وM2 و M3 .كما بينت النتائج ان للسرعة العملية والتداخل بينها وبين تراكيب آلات الحرثة المركبة تأثيراَ معنوياَ ($p<0.05$) في جميع الصفات المدروسة.

الكلمات المفتاحية: آلة الحراثة المركبة، قوة السحب، الكفاءة الحقلية، استهلاك الوقود، دليل التفتيت للتربة.