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DRAFT FORCE AND EFFICIENCY OF SOIL LOOSENING FOR DIFFERENT DESIGNS OF SUBSOILER PLOW SHANKS

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ABSTRACT

Many farmers resort to using subsoiler plows with a straight shank to alleviate soil compaction, but require a high draft. To process these problems subsoilers with bent and curved shanks have been designed and manufactured. In the current study, the efficiency of soil loosening (cm^2. kN^{-1}), draft force (kN), wasted power due to slippage (kW), fuel consumption ($L.ha.^{-1}$), and disturbed area (m^2) was investigated for two soil textures (silty clay and silty loam), three types of shanks (straight, curved, and bent), and three tillage depths (35,45, and 55) cm. The results show the superiority of the bent shank at a tillage depth (35) cm in both soil types, registered less draft force, fuel consumption, and wasted power due to slippage compared to straight and curved shanks. Also, the bent shank recorded the highest efficiency of soil loosening at a tillage depth (35) cm in both soil types. Besides that, the bent shank at a depth of (35) cm in both soil types achieved the highest disturbed area. Moreover, at all tillage depths in both soil types, the bent shank reduced the draft force, fuel consumption, and wasted power by slippage by (30%, 19%), (19%, 10%), and (30%,15%) compared to the straight and curved shanks, respectively. While at all tillage depths in both soil types, the bent shank increased the disturbance area and efficiency of soil loosing by (7%, 4%) and (15%, 5%) compared to the straight and curved shanks, respectively.

INTRODUCTION

At present, the agricultural sector in Iraq is confronted with challenges about the sustainable production of food and the escalating expenses associated with farming operations (Hilal *et al.*, 2021). These challenges have been exacerbated by the ramifications of the COVID-19 pandemic, which the nation has contended with since the onset of 2020 and persists to do so up to the present juncture (Saleh *et al.*, 2022). In addition, other essential issues about climate change have started to alter conventional farming methods (Dahham *et al.*, 2023). On the other hand, conservation agriculture has been introduced in Iraq to reduce soil compaction (Al-Shammary *et al.*, 2023; Mirpanahi *et al.*, 2023), but it requires several years to be widely implemented on farms (Hilal *et al.*, 2023). Consequently, farmers continue to use the same implements at the same tillage depths in successive operations, leading to soil compaction and the subsequent deterioration of the soil biological, chemical, and physical characteristics (Keller *et al.*, 2019; Wang *et al.*, 2023; Wang, Fu, *et al.*, 2021). Moreover, the formation of hardpan layers beneath the soil is an affecting factor in reducing water permeability and hindering drainage, affecting the root zone and hampering its expansion (Celik and Raper, 2016; Islam *et al.*, 2023; Obour *et al.*, 2018; Zhang *et al.*, 2023). To address these issues, these soils require high mechanical capabilities to break through these layers. The adoption of subsoiler plows or deep plows is considered one of the most important methods to solve this problem (Lou *et al.*, 2021; Song *et al.*, 2022; Spoor, 2006).

Deep tillage, also known as subsoiling is an agricultural technique that utilizes a specialized tool called a subsoiler (Zhao *et al.*, 2023). Its primary objective is to disrupt compacted soil layers at depths ranging from 25 to 60 cm, creating spaced channels from 60 to 150 cm without inverting the soil, this is achieved by employing blade-like shanks drawn through the soil, forming continuous furrows (Martlew *et al.*, 2023; Xia Li and Dongxing Zhang, 2012).

Many shank shapes that used with a subsoiler, where the shape of the shank affects methods of subsoiler work, including draft force, surface disturbance, and effectiveness in fracturing soil (Sun *et al.*, 2018; Tong *et al.*, 2020; Wang, Li, *et al.*, 2021), example shapes are bent shank, curved shank, straight shank, colter with blades and reversing subsoiler, colter with blades subsoiler, colter subsoiler, vibration and non-vibration types, winged type and no-wing type, parabolic shank, and semi-parabolic shank (Odey *et al.*, 2018).

Numerous studies have demonstrated that utilizing a bent shank for a subsoiler plow constitutes an efficacious approach to diminishing the draft force, while concurrently augmenting the extent of soil disturbance (Durairaj and Balasubramanian, 1997; Durairaj and Kumar, 1999; H. P. Harrison, 1990). According to Raper (2007), three types of shank subsoiler plows were compared: Paratill, Terramax, and KMC. The shanks exhibited drawbar power of 40, 38, and 41kW respectively at a depth of 40cm and a forward speed of 4 km.h^{-1}.Nassir (2022) pointed out an increase in the draft force by increasing the plowing depth, this was observed when investigating the impact of the plowing depth from 35 to 65cm for two types of subsoiler plows, those with curved and straight shanks, the draft force increased by 18.979 and 20.163 kN respectively. Odeyet *al.* (2018) found, that when studying various shapes of shanks subsoiler plow, the bent shank recorded a draft force of 4581.02 N at a depth of 40cm.Meanwhile, the straight and straight shanks with wings recorded draft force of 7385.28 N and 7003.4 N respectively at the same depth.

According to Godwin (2007) and Shahgoli *et al.* (2010) , the efficiency of soil loosening (ESL) stands as a pivotal criterion in determining the optimal operation indexes for a plowing equipment. As the subsoiler moves through the soil, the shank works to loosen the soil, resulting in increased soil aeration and improved root penetration, the efficiency of this soil loosening process is a crucial factor in evaluating the performance of tillage tools (Salar *et al.*, 2013). Moreover, soil type plays a pivotal role in determining the efficiency of the subsoiling process. Different soil textures and compositions may require varying levels of force to achieve the desired loosening effect (Dahham, 2018). Understanding the specific characteristics of the soil being worked on is crucial for achieving optimal results (Wang, Li, *et al.*, 2021).

In this paper, the first objective was to the problem of the high requirement for the straight shank of the subsoiler plow from the draft force, to process this problem subsoilers with bent and curved shanks have been manufactured and designed. The second objective was to investigate these shanks in two soil types (silty clay and silty loam) and three tillage depths 35, 45, and 55cm, and the effect these in the efficiency of soil loosening, draft force, wasted power due to slippage, fuel consumption, and disturbed area.

MATERIALS AND METHODS

Field description

The study was carried out in two soil types at fields located within the region of Tel kaif, less than 13km from Mosul city (36°29'22"N 43°7'9"E), north Iraq. The first field soil had a texture of silty clay, and the second field soil had a texture of silty loam shown in Table 1. The fields used several previous seasons to grow the wheat crop. The soil separators were estimated using the pipette method as described by (Blake and Hartge, 2018).

Table (1): Fields soil texture

Fields	Soil Texture	Sand(mg.kg^{-1})	Clay(mg.kg^{-1})	Silt(mg.kg^{-1})
1st field	Silty Clay	124.22	460.78	415
2nd field	Silty Loam	270.50	210.75	518.75

A variety of laboratory tests were performed on soil samples for five soil depths. The soil penetration index was collected using the hydraulic penetrometer the methods described by (Birl and Morrison, 2018). The soil bulk density and soil moisture content were collected using the procedures outlined in (Donald, 1987). The results are shown in Figure (1).

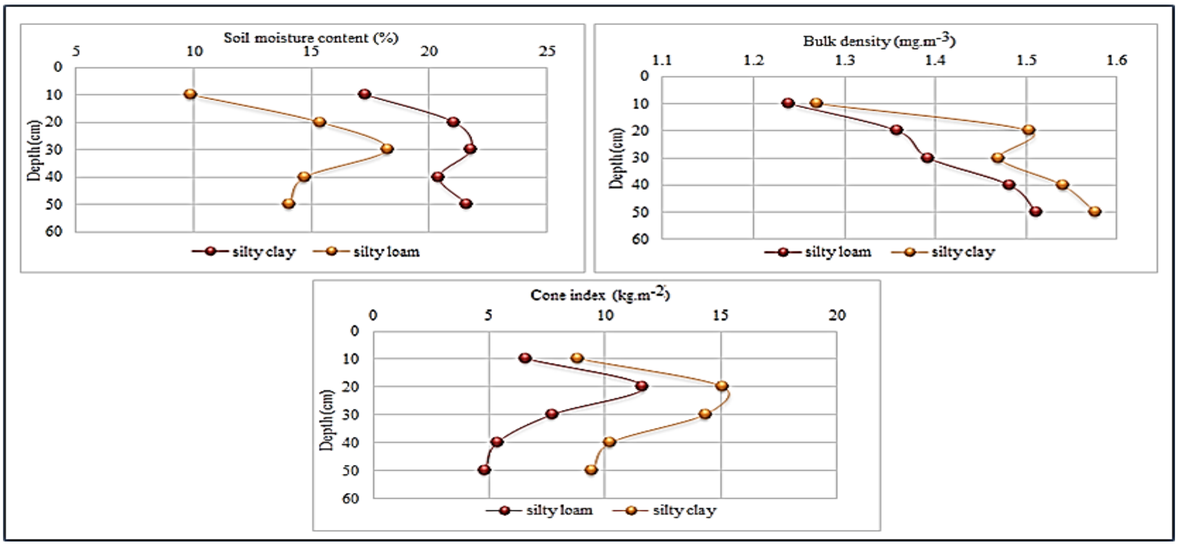

Figure (1): Soil physical properties at Telkef fields

Description of Subsoiler Shanks

The study encompassed the utilization of three types of shanks for the subsoiler single-tine plow, the three types of shanks designed were: straight shank, curved shank, and bent shank. These shank models were created using AutoCAD 2010 software, as exemplified in figure (2).

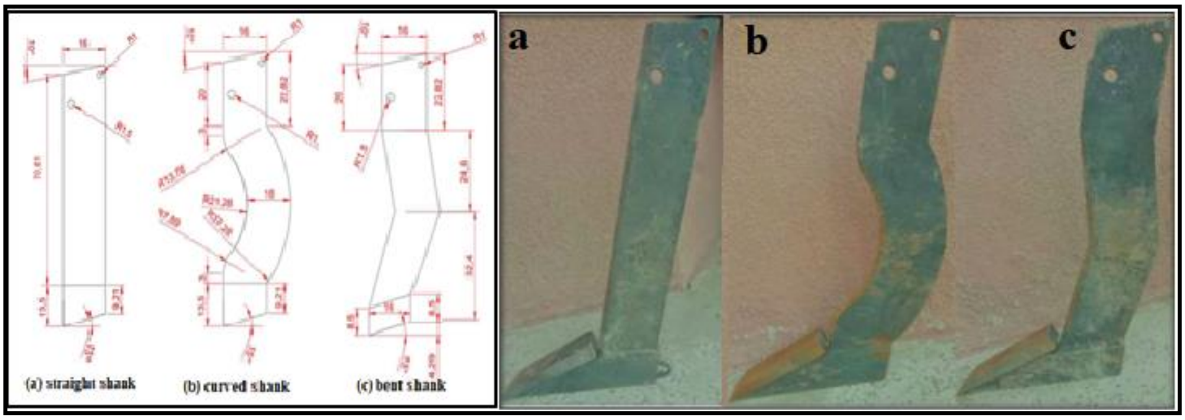

Figure (2): The scheme subsoiler shanks
(a) straight shank (b) curved shank (c) bent shank

Design explanation of the experiment

The experiment was factorial, involving three factors: soil type, tillage depth, and shank type. It was carried out using a randomized complete block design (RCBD) with a split-split plot layout. The experiment encompassed 2×3×3×3= (45) different combinations. The length of the refined treatments was 30m. The treatment results underwent testing utilizing the Duncan test, with a significance level of 0.05. The experiments were executed at a forward speed of 3.7 km.h^{-1}.

Following trials on various shank types with different tillage depths in diverse soil types, three locations were randomly chosen within each treatment. The soil was excavated meticulously to prevent any failure on both sides of the channel. The disturbed area was determined using the subsequent equation (Spoor and Godwin, 1978):

$$A = S \times DC \times W \times D$$

Where: *A:* disturbed area (m^2); *S:* represents the extent of the disturbed soil on either side of the trench (m); *DC:* critical depth (m); *W:* width of the trench at depth (m); *D:* tillage depth (m).

Draft force (kN)

Two tractors were utilized in the experiments: one with a subsoiler attachment (forming a subsoiler-tractor combination), and the other tasked with towing this combined unit (using the towing method). The towing tractor is a NEW HOLLAND TD95D, equipped with a 4-cylinder engine of 98hp. The second tractor, an MF model, is also equipped with 4-cylinder engine 67 hp. Its primary role in the experiments was to facilitate the raising and lowering of the implement; consequently, its gearbox remained in a neutral position throughout the trials. The draft force was measured using a digital dynamometer. The draft force was calculated using the following equation:

$$F = H - R$$

Where: *R:* denotes the rolling resistance of the rear wheel of the tractor (kN); *H:* signifies the thrust exerted by the rear wheel of the tractor (kN); *F:* represents the draft force (kN).

Wasted power by slippage (kW)

The equation for calculating wasted power by slippage is (Al-Jarrah, 2011):

$$W_{ps} = \frac{F \times (V_t - V_p)}{3.6}$$

Where: W_{ps}: wasted power by slippage (kW); *F:* draft force (kN); V_t: theoretical speed (km.h^{-1}); V_p: practical speed (km.h^{-1}).

Fuel consumption (L.ha. $^{-1}$): The amount of fuel consumed was calculated using a locally manufactured fuel consumption device as follows:

$$Fc = \frac{FC_a \times 10000}{B_p \times S \times 1000}$$

Where: *FC:* fuel consumption (L.ha. $^{-1}$); B_p: tillage actual working width (m); FC_a: the amount of the fuel consumption during the process (mL); *S:* distance length (m).

The efficiency of soil loosening (cm^2. kN^{-1}): The efficiency of soil loosening (ESL) can be computed using the following equation (Salar *et al.*, 2021):

$$ESL = \frac{A}{F}$$

Where: F: draft force (kN); A: the loosening soil area (cm^2).

Figure (3): The tillage result using three types of shanks in the field.
(a) bent shank (b)curved shank (c) straight shank

RESULTS AND DISCUSSION

Draft force (kN)

Table (2) shows the effect of shank type on the draft force, at three different tillage depths of 35,45, and 55cm, the results showed there were significant differences ($p<0.05$) in draft force at the shank type and different combinations of tillage depths.

Table (2): Effect of shank type on the draft force *(kN)*, at three different tillage depths

Shank type	Tillage depth			Unit
	35	45	55	*cm*
Curved	13.46 e	14.54 d	17.27 b	*kN*
Straight	15.00 d	15.95 c	18.86 a	*kN*
Bent	11.21 g	12.25 f	15.94 c	*kN*

As depicted in Figure (4), the draft force of straight, curved, and bent shanks increased significantly ($p<0.05$) as the tillage depth increased in both soil types. For example, the draft force for the curved shank increased from 10.86 to 15.63 kN when the tillage depth increased from 35 to 55cm in silty loam soil, while for the curved shank in silty clay at the same depths, the draft force increased from 13.06 to 17.90

kN. This can be attributed to the difference in soil hardness and resistance to movement in front of the shank due to varying values of cohesive force, soil bulk density, and the angle of internal friction of the soil between the two soil types. Besides that, increasing the depth means increasing the plow area facing the soil and stirring up a larger amount of soil, thus increasing the force required for pulling (Raper and Bergtold, 2007).

Furthermore, the results indicated that the bent shank at a depth of 35cm in silty loam soil achieved the lowest draft at 8.49 kN, while the straight shank at a depth of 55cm in silty clay soil recorded the highest draft force at 19.67 kN. This can be attributed to differences in shank geometry, where the horizontal distance between the tine nose and the vertical level of the bent shank is greater compared to other shanks. This allows for better penetration and soil breaking by the tine, when the soil encounters the bent shank, its bending action helps apart soil clods, resulting in a reduced draft force requirement (Tong *et al.*, 2020).

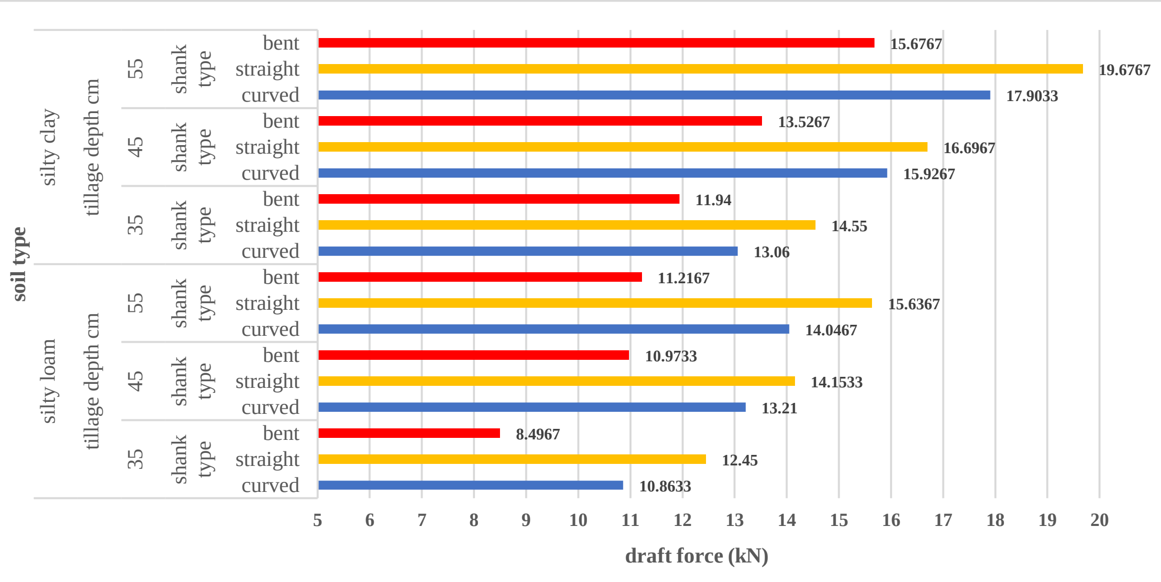

Figure (4): the draft force of subsoiler shanks at soil types and tillage depths.

Fuel consumption (L. ha^{-1})

Table (3) shows statistically significant differences in the effect of the interaction between the shank type and tillage depths on fuel consumption.

Table (3): Effect of shank type on fuel consumption (*L. ha^{-1}*), at three different tillage depths

Shank type	Tillage depth			Unit
	35	45	55	*cm*
Curved	13.19 e	15.81 c	16.49 b	*L.ha^{-1}*
Straight	14.47 d	16.89 b	17.10 a	*L.ha^{-1}*
Bent	11.73 f	13.39 e	14.96 d	*L.ha^{-1}*

As depicted in Figure (5), the fuel consumption of straight, curved, and bent shanks increased significantly ($p<0.05$) as the tillage depth increased in both soil types. For example, the fuel consumption for the straight shank increased from 14.94 to 16.54 L. ha^{-1} when the tillage depth increased from 35 to 55cm on silty loam soil, while for the straight shank in silty clay soil at the same depths, the fuel consumption increased from 15.11 to 17.05 L. ha^{-1}. The reason for this is due to the lower required draft force and slippage at the first soil compared to the second soil, fuel consumption depends on the pulling force and slippage (Yahya, 2023).

Furthermore, the results indicated that the bent shank at a depth of 35cm in silty loam soil achieved the lowest fuel consumption at 12.47 L. ha^{-1}, while the straight shank at a depth of 55cm in silty clay soil recorded the highest fuel consumption at 17.05 L. ha^{-1}. The reason for this is due to the lower draft force and slippage at the bent shank compared to the other shanks.

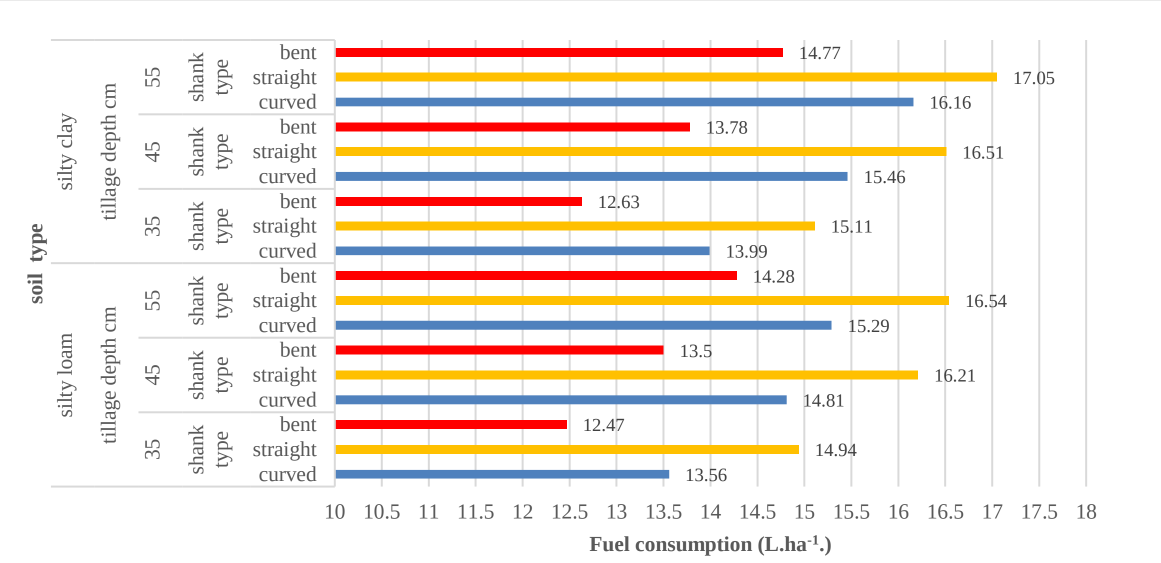

Figure (5): the fuel consumption of subsoiler shanks at soil types and tillage depths.

Wasted power by slippage (kW)

Table (4) shows the effect of shank type on wasted power by slippage at three different tillage depths of 35, 45, and 55cm. The results indicate significant differences ($p<0.05$) in wasted power by slippage based on the shank type and various combinations of tillage depths. This is back to the reason that the force wasted by slippage is affect by the draft force and slippage, both of which increase with increasing tillage depth (Taghavifar and Mardani, 2015).

Table (4): Effect of shank type on wasted power by slippage *(kW)*, at three different tillage depths

Shank type	Tillage depth			Unit
	35	45	55	*cm*
Curved	0.8083hg	2.4000e	5.8933b	*kW*
Straight	1.1867g	2.9283d	6.7667a	*kW*
Bent	0.7117h	1.0150f	4.7367c	*kW*

As depicted in Figure (6), the slippage related power wasted of straight, curved, and bent shanks significantly ($p<0.05$) increased as the tillage depth increased in both soil types. For example, the slippage related power wasted for the curved shank increased from 1.274 to 4.391 kW when the tillage depth increased from 35 to 55cm in silty loam soil. In silty clay soil at the same depths, the slippage related power wasted increased from 1.888 to 5.426 kW.

Furthermore, it was observed that the straight shank at a depth of 55cm in silty clay soil recorded the highest slippage related power wasted, reaching 5.977 kW. Additionally, the results indicated that the bent shank at a depth of 35cm in silty loam soil achieved the lowest slippage related power wasted at 1.059 kW. The reason for this is that the bent shank shape worked to decrease the resistance of the soil towards the plow during tillage. Consequently, draft force and slippage decrease, leading to a reduction in wasted power due to slippage.

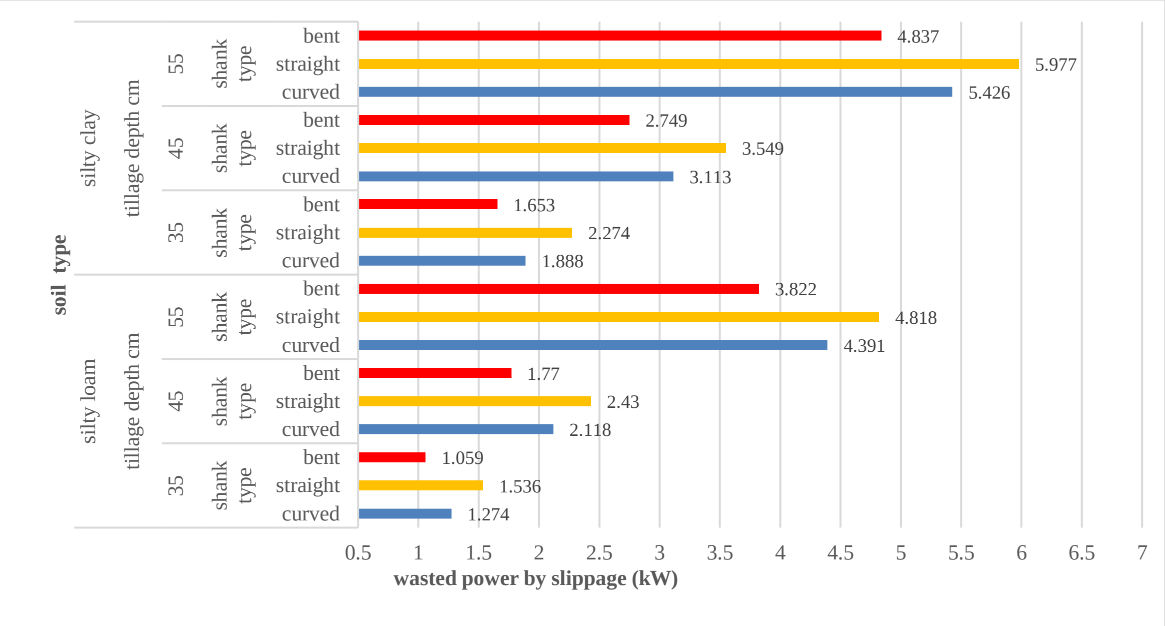

Figure (6): the wasted power by slippage of subsoiler shanks at soil types and tillage depths.

Disturbance area (m^2)

When using the subsoiler plow, there are two types of disruption or breakdown: crescent disruption occurs near the surface, where the soil moves forward, sidewards, and upwards, expanding its spread and porosity while reducing its density. Conversely, the other type of disruption (compact breakdown) occurs at greater depth, where the soil only moves forward and sideways, resulting in soil compression, reduced porosity, and increased density. These two types of disruption are distinguished by a critical depth known as the critical depth. Below this depth, the soil merely shifts forward and sideways (Spoor and Godwin, 1978).

In this study, Table (5) shows the effect of shank type on the disturbance area at three different tillage depths 35, 45, and 55cm. The results revealed significant variations ($p<0.05$) in the disturbance area based on the shank type and different combinations of tillage depths.

Table (5): Effect of shank type on disturbance area *(m^2)*, at three different tillage depths

Shank type	Tillage depth			Unit
	35	45	55	*cm*
Curved	0.1190de	0.1191de	0.1225c	*m^2*
Straight	0.1125f	0.1145f	0.1180e	*m^2*
Bent	0.1215dc	0.1265b	0.1300a	*m^2*

As depicted in Figure (7), the disturbed area of straight, curved, and bent shanks significantly increased ($p<0.05$) as the tillage depth increased in both soil types. For example, the disturbed area for the curved shank increased from 0.1165 to 0.1212 m^2 when the tillage depth increased from 35 to 55cm in silty loam soil. IN silty clay soil at the same depths, the disturbance area increased from 0.117 to 0.1227 m^2. This result is in agreement with (R. L. Raper, 2005).

Furthermore, it was observed that the bent shank at a depth of 55cm in silty clay soil achieved the highest disturbance area, reaching 0.1272 m^2. Additionally, the results indicated that the straight shank at a depth of 35cm in silty clay soil recorded the lowest disturbance area at 0.1125m^2. The reason is that the bent shank shape works to push the critical depth further away from the surface. This leads to an increase in the cross-sectional area of the collapsed region compared to other shanks. This result is in agreement with (Aday and Ramadhan, 2019).

Figure (7): the disturbed area of subsoiler shanks at soil types and tillage depths.

The efficiency of soil loosing (cm^2. kN^{-1})

Soil loosening efficiency can be defined as the ratio of the disturbed soil volume to the draft force exerted by the tractor during the subsoiling operation, this metric serves as a key criterion for assessing the work efficiency of tillage tools (Salar *et al.*, 2021).

The effect type shanks on the efficiency of soil loosing at three different tillage depths 35,45, and 55cm are illustrated in Table (6). The results revealed significant variations ($p<0.05$) in the efficiency of soil loosing based on the shank type and different levels of tillage depths.

As depicted in Figure (8), the bent shank surpassed curved and straight shank in both soil types under different tillage depths by achieving the highest for soil loosening, reach (93.81) cm^2. kN^{-1}, while the straight shank at a depth of 55cm in silty loam soil recorded the lowest efficiency of soil loosening (65.64) cm^2. kN^{-1}. This difference can be attributed to the rate of soil disturbance increasing more than the draft force for the bent shank compared to the straight and curved shanks, increasing the efficiency of soil loosening (Salar *et al.*, 2021).

Table (6): Effect of shank type on the efficiency of soil loosing (*cm*^{2}. *kN*$^{-1}$), at three different tillage depths

Shank type	Tillage depth			Unit
	35	45	55	*cm*
Curved	90.95b	85.73c	68.35f	$cm^2. kN^{-1}$
Straight	76.37d	74.00e	61.17g	$cm^2. kN^{-1}$
Bent	95.48a	90.62b	75.12ed	$cm^2. kN^{-1}$

Furthermore, ESL for straight, curved, and bent shanks significantly decreased as the tillage depth increased in both soil types. For example, ESL for the curved shank decreased from 89.66 to 72.36 cm^2. kN^{-1}. This decrease can be referred to as increased soil bulk density with increasing depth. Additionally, ESL varied between the soil types due to differing values of cohesion force, soil bulk density, and the angle of internal friction (Salar *et al.*, 2013).

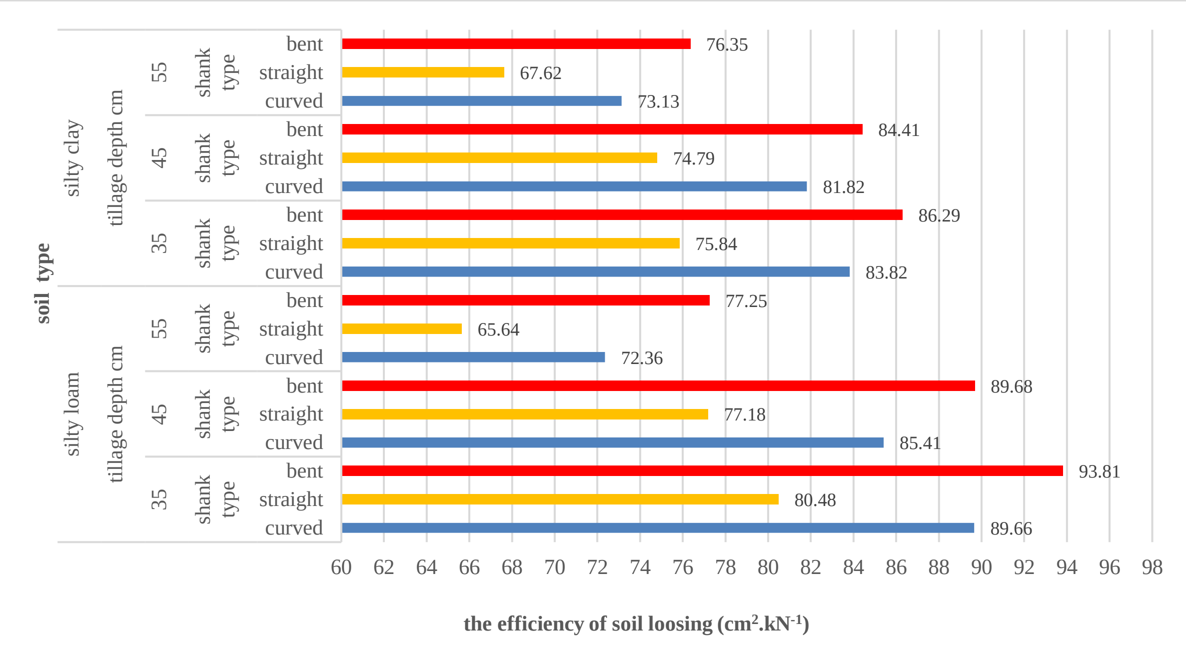

Figure (8): the efficiency of soil loosening of subsoiler shanks at soil types and tillage depths.

CONCLUSIONS

The research shows the conclusions reached:

1- The bent shank had the lowest draft force, fuel consumption, and wasted power by slippage as compared to the straight and curved shanks for both soil types, the results were: In silty loam soil at tillage depth 35cm were (8.49) kN, (12.47) L. ha^{-1}, and (1.059) kW, respectively. While in silty clay soil at the same depth were (11.94) kN, (12.63) L. ha^{-1}, and (1.65) kW, respectively.

2- The bent shank had the highest disturbance area as compared to the straight and curved shanks for both soil types, the results were: In silty loam at tillage depth of 55cm was 0.1257m^2, while in silty clay at the same depth was 0.1272m^2.

3- The bent shank had the highest efficiency of soil loosing as compared to the straight and curved shanks for both soil types, the results were: In silty loam soil at tillage depth 35cm was 93.81 $cm^2.kN^{-1}$, while in silty clay soil at the same depth was 86.29 $cm^2.kN^{-1}$.

Finally, the study recommends the possibility of depending on the bent shank to treat and reduce soil compaction, as it requires minimal energy requirements, in addition to its high efficiency in loosening the soil compared to others shanks.

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CONFLICT OF INTEREST

The authors state that there are no conflicts of interest with the publication of this work.

قوة الجر وكفاءة تفكيك التربة لقصبات ذات تصاميم مختلفة لمحراث تحت التربة

مثنى عبدالمالك نوري الجراح [1]، غزوان احمد دحام [1]، حسين عبد حمود [1]
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الخلاصة

يلجأ العديد من المزارعين إلى استخدام محراث تحت التربة ذات القصبات المستقيمة للتقليل من كبس التربة، ولكنها تتطلب قوة سحب عالية. لمعالجة هذه المشكلة، تم تصميم وتصنيع نوعين من قصبات محراث تحت التربة هما القصبة المقوسة والقصبة المنحنية، من خلال دراسة تأثير مستويين من نسجة التربة (غرينية مزيجية وغرينية طينية) وثلاث مستويات من اعماق الحراثة (35، 45، 55) سم وثلاث اشكال لقصبات محراث تحت التربة (مستقيمة، مقوسة، منحنية) وتأثير ذلك في كل من كفاءة تفكيك التربة (سم^2 .كيلونيوتن$^{-1}$) وقوة الجر (كيلو نيوتن) والطاقة المفقودة بسبب الانزلاق (كيلو واط) واستهلاك الوقود (لتر.هكتار$^{-1}$) والمساحة المثارة (متر مربع). أشارت النتائج إلى وجود فروقات معنوية لجميع الصفات تحت القصبة المنحنية مقارنة بالقصبات المستقيمة والمقوسة في كلا نوعي التربة. بالإضافة إلى ذلك أشارت النتائج إلى تفوق القصبة المنحنية في كلا نوعي التربة عند عمق حراثة 35 سم في تسجيل اقل قوة سحب واستهلاك وقود وطاقة مفقودة بسبب الانزلاق. كما سجلت القصبة المنحنية أيضًا أعلى كفاءة في تفكيك التربة عند عمق حرث 35 سم في كلا نوعي التربة. في حين حققت القصبة المنحنية عند عمق 35 سم في كلا نوعي التربة أعلى مساحة مثارة للتربة. علاوة على ذلك، في جميع أعماق الحرث في كلا نوعي التربة، قلل الساق المنحني من قوة السحب واستهلاك الوقود والطاقة المفقودة بسبب الانزلاق بنسبة (30%، 19%)، (19%، 10%)، و (30%، 15%) مقارنة بالساق المستقيمة والمنحنية على التوالي. بينما، في جميع أعماق الحرث في كلا نوعي التربة، زاد الساق المنحني من مساحة التربة المثارة و كفاءة تفكيك التربة بنسبة (7%، 4%) و (15%، 5%) مقارنة بالساق المستقيمة والمنحنية على التوالي.

الكلمات المفتاحية: قوة السحب، كفاءة تفكيك التربة، محراث تحت التربة، استهلاك الوقود، المساحة المثارة.

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