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Study of Power Requirements of the Combined Moldboard Plow at Different Forward Speeds

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Abstract

The experiments were carried out in one of the agricultural fields of the College of Agriculture, University of Basrah, using a split-plot design with three replications to study the influences of single factors and their interactions on the performance of the developed moldboard plow. The parameters studied involved: moldboard type (M1: conventional moldboard, M2: finned moldboard), rigid harrow types (H0: moldboard plow without rigid harrow, H1: moldboard plow with one row of rigid harrow, H2: moldboard plow with two rigid harrows) and forward speed (S1: 1.5 km h^{-1}, S2: 2.5 km h^{-1}, S3: 3.5 km h^{-1}). The results showed a significant effect of individual factors on the performance variables. The moldboard with fins (M2) led to an increase in draft force (%$p<0.05$) compared to the conventional moldboard (M1) by 8.36%. H2 increased the draft force, reaching 17.60 kN compared to H0 by 35.18%. Forward speed had a significant effect (%$p<0.05$), whereas draft force increased from 16.86 kN to 14.04 kN when forward speed from 1.5 to 3.5 km h^{-1}. The interactions were also significant (%$p<0.05$). The interaction treatment (M2*H2*S3) recorded the highest draft force value of 19.86 kN, while the interaction treatment (M1*H0*S1) recorded the lowest value of 10.55 kN. Furthermore, the highest slip percentage was observed with (M2*H2*S3) reaching 19.53%, while the lowest was observed with (M1H0S1) at 8.2%. In terms of fuel consumption, the combination (M2*H2*S1) recorded the highest rate at 35.37 L ha^{-1}, while the combination (M1*H0*S3) recorded the lowest fuel consumption rate at 16.60 L ha^{-1}.

Keywords: Fins, rigid harrow, conventional moldboard, draft force, fuel consumption

I. Introduction

The tillage operation is the basis of agricultural operations to prepare the seedbed by loosening, inverting, and pulverizing the soil blocks. The energy spent on the plow must be used with optimal efficiency and productivity, while the energy necessary for soil tillage should be minimized (Okoko et al. 2018). The moldboard plow is one of Iraq's most widely used plows, particularly for plowing heavy soils. The moldboard plow cuts and breaks up, and inverts the soil blocks in the large and irregularly shaped blocks. Large soil blocks require pulverizing by secondary harrowing machines after plowing with this type of plow, therefore repeating the passing times in the field to obtain the suitable seedbed (Muhsin, 2017a; Nassir, 2016). Soil preparation using traditional methods through the individual use of tillage machines can cause the formation of compacted soil layers and an increase in the bulk density of the soil, as well as resistance to penetration of the soil. This hinders the penetration and spread of plant roots in the soil and the prevalence of anaerobic conditions in the compacted soil layer. The hard soil layers reduce water movement in the soil body and increase the accumulated salts in the root zone, negatively affecting plant growth and production (Li et al., 2022). The tillage operations in their various types are considered one of the important processes carried out in the field due to their great importance in improving soil properties, which is positively reflected in preparing the appropriate conditions for seed germination. However, increasing the number of times agricultural machinery passes in the field results in increased soil compaction reflecting negative effects on the structure and physical properties of the soil. Compacted soil has direct effects on the growth and production of plants. Therefore, preparing the soil by combined tillage machines could reduce passes in the agricultural field is one of the modern basics followed in shortening time, effort, and costs and reducing the negative impact of the plowing process (Jassim, 2018; Salama et al., 2018; Nassir, 2023).

Developing agricultural machines, particularly soil preparation machines, is one of the methods many designers and manufacturers of soil preparation machines resort to to improve soil properties to be more suitable for plant growth (Abou Hussien et al., 2020). The good developments in moldboard plows are one of the important factors that work to reduce the values of the pulverization index.

The moldboards differ in length, width, and degree of bending, and on this basis, their ability to turn the soil slice, whether completely or partially Most moldboard types leave large soil blocks on the soil surface and an irregular plowing appearance (Jassim, 2018). Adding harrow to the moldboard plow reduces the fragmentation index with a single pass through the field, and the degree of soil harrowing depends on the engineering design of the harrows, whether disc, reciprocating or rigid (Nasser, 2014). The forward speed of the tractor plays an important role in the difference in the values of the fragmentation index, which, when increased, reduces the soil fragmentation index through the collision of soil blocks with each other and with the plow blade due to the increasing kinetic energy (Mohsen, 2017, Alele, 2019, Gilandeh et al., 2022).

The problem of forming large soil clods when plowing with a moldboard plow is one of the main reasons for performing secondary plowing using soil preparation machines that work to break up large soil clods produced by the plowing process. Many passes of agricultural tractors in the field result in more fuel consumption and greater compaction. This increases the economic aspect required to prepare the field for cultivation. To solve these problems, one can use a combined moldboard plow to improve its ability to produce a suitable seedbed through a single pass in the field.

The experiment aimed to study the mechanical performance indicators of the developed rotary plow represented by the pulling force and the percentage of slippage, to calculate the practical productivity and the amount of fuel consumed, and to measure the soil pulverization index in addition to studying some physical properties of the soil after using the developed moldboard plow.

I. Material and Methods

Description of developed moldboard plow

The traditional plow was developed in the workshop of the Department of Agricultural Machinery and Equipment in the College of Agriculture of the University of Basra, by providing it with fins and a rigid harrow for breaking up (Fig. 1). A double-moldboard plow manufactured by the General Company for Mechanical Industries. The moldboard is of the semi-helical type. Each moldboard had a width, height, and concavity of 45 cm, 40 cm, and 5.6 degrees respectively. These moldboards are characterized by their high ability to break up the soil. The moldboards have a cutting knife with dimensions of (9*44) cm. The knife cutting angle is 28 degrees. The six fins were fixed on the surface of the moldboard. The fins with dimensions and measurements were determined through a field experiment. The plow was also provided with a tandem of mutually rigid harrows connected to the plow body in a hinged manner. The first row was placed 20 cm away and parallel to the line of the two plows. The second row was placed 15 cm away from the first row. The length of each harrow was 180 cm with 13 rigid tines.

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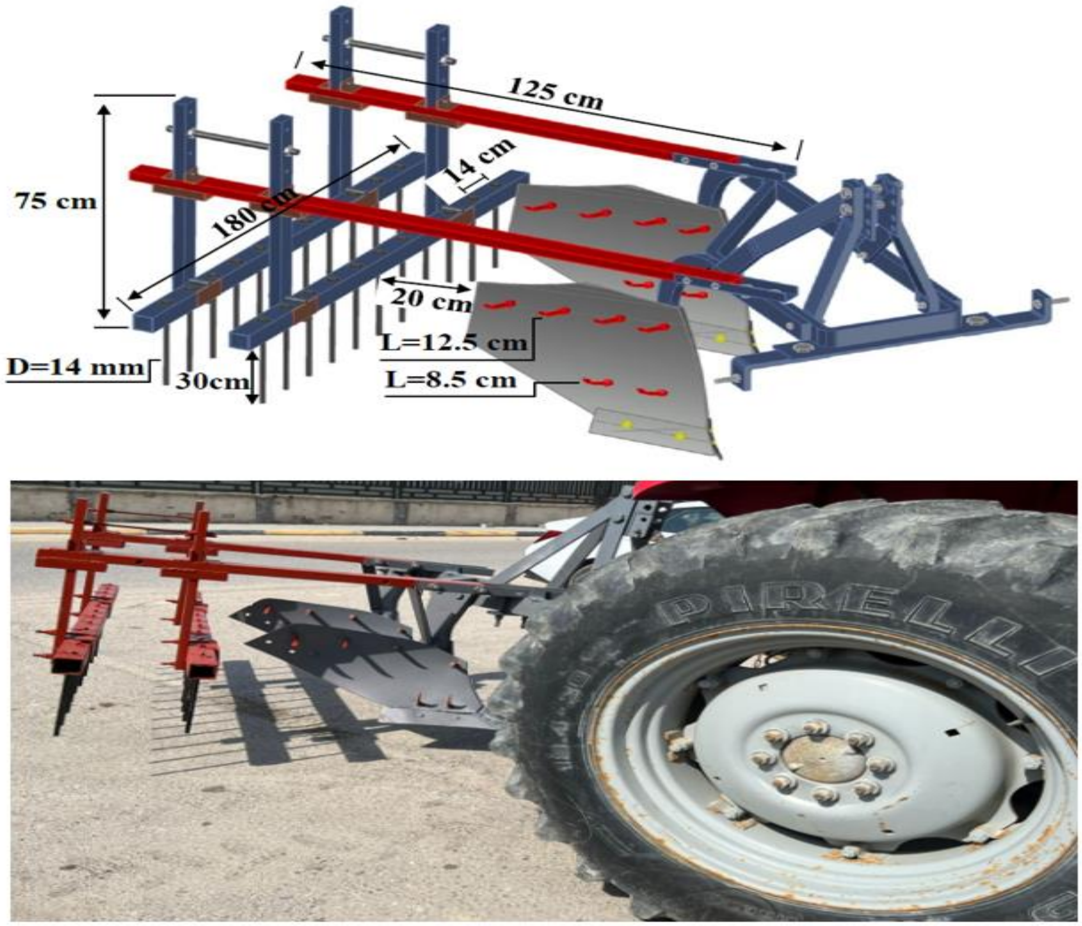

Figure 1. Devolved moldboard plow

Soil properties and texture

The soil moisture content and soil density were determined by taking samples from the field at soil depths of 0-15, 15-20, and 20-25 cm with three replicates for different soils using the Core. The samples were dried in the oven at a temperature of (105°C) for 24 hours, then the moisture percentage was calculated based on dry weight, and the apparent density of the soil was calculated according to the method described in Black et al. (1965). The soil texture was estimated by the absorbent method according to the method mentioned in Black et al. (1965) to determine the soil texture in which the experiments were carried out and all the results are shown in Table (1).

Table 1. The initial soil properties and texture

	Soil depth		
Soil properties	0-15	15-20	20-25
Soil moisture content (%)	10.23%	16.47%	24.68%
Bulk Density (Mg m^{--3})	1.29	1.33	1.41
Porosity (%)	11.5	14.80	22.70
Penetration Resistance (kN m^{-2})	1948.57	2147.36	2344.73

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Cohesion (kN m^{-2})	15.41	11.39	13.58
Adhesion (kN m^{-2})	0.15	0.18	0.26
Soil texture	**Clay%**	**Silt%**	**Sand %**
	35	47	18
Silty loamy soil			

Agricultural Tractors

CASE JX75T Tractor

CASE JX75T tractor is Turkish-made and equipped with a 4-cylinder 4-stroke diesel engine that generates rear-wheel drive or front-wheel assistance MFWD with a design power of 55 kW. The weight of the tractor is 3059.15 kg. The maximum weight that its hydraulic system can handle is 2000 kg force. The tractor was used to connect the installed machine through the hydraulic system to control the depth of the machine. The tractor gearbox was put in neutral and its engine was left running to operate the hydraulic system without the tractor having any role in pulling the installed machine.

Massey-Ferguson 440 xtra tractor

The Massey-Ferguson 440 xtra tractor is Brazilian-made and equipped with a four-cylinder four-stroke diesel engine that generates rear-wheel drive or front-wheel assistance MFWD. Its design power is 65.5 kW. The tractor weighs 3430 kg. The Massey-Ferguson 440 xtra tractor was used to pull the CASE JX75T tractor, and the machine was attached to it with a flexible cable that can withstand the high tensile forces applied to it when pulling. The engine speed of the Massey-Ferguson 440 xtra tractor was fixed at 1500 rpm.

Load cell

The electronic load cell (Fig. 2) was used to measure the draft force of the soil preparation machine with different compositions and at the forward speeds used in field experiments. The device was manufactured by Futek in the United States of America in 2010. Its model is Cylinder. S—Beam, and the model is LSB 600. The load cell was connected to a laptop computer via a USB data cable to record and store the measured data in the Excel software.

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1- Load cell 2- Portable computer 3-Data transfer wire Device 4- mounting points on the pull source and load source 5 software for recording and saving data on the computer.

Figure (2) Draft force measuring device (Load Cell).

Draft force measurement

The draft force of the compound tiller was measured using a load cell device (Appendix 2). The load cell was attached to the pulling shaft of the Massey- Ferguson axtra 440 tractor and the front of the CASE JX75T tractor and the machine attached to it were connected to the other end of the load cell using a flexible steel wire. The CASE JX75T tractor and the machine attached to it were pulled by the Massey- Ferguson axtra 440 tractor for a distance of 5 m to reach the required plowing depth and stabilize the tractor speed. The engine speed of the Massey- Ferguson axtra 440 tractor was set at 1500 rpm. The draft force was then measured for a longitudinal distance of 20 m, which is the length of the experimental unit, and the draft force readings were recorded and saved by a laptop computer for all tillage parameters (machine, its components, and forward speed). The rolling resistance of the CASE JX75T tractor was also measured by pulling it while the machine was lifted by its hydraulic device for a distance of 20 m. The rolling resistance values were recorded for all experimental parameters. The draft force was calculated from Equation 1 taken from Mckyes (1985). The process was repeated three times for each tillage parameter.

$$F = Ft - R \qquad (1)$$

Where: F: Draft force (kN), Ft: Total draft force (kN), R: Rolling resistance of the CASE JX75T tractor (kN).

Fuel consumption measurement device

The fuel consumption meter (Fig.3) was used for the Massey-Ferguson 440 xtra tractor. The device consists of a set of rubber tubes, connections, and a graduated cylinder with a capacity of 100 cm3. The cylinder was filled with fuel from a 3-litre tank fixed above the graduated cylinder. The graduated cylinder was supplied with fuel by a rubber tube with a conical valve located directly above the graduated cylinder which, when opened, allows fuel to flow into the graduated cylinder. This cylinder was connected from below to the fuel feed pump, which is one of the parts of the fuel system in the tractor. The excess fuel from the injectors was delivered via a rubber tube to the graduated cylinder. The graduated cylinder and fuel tank were fixed to a wooden board and the latter was fixed to the front of the tractor.

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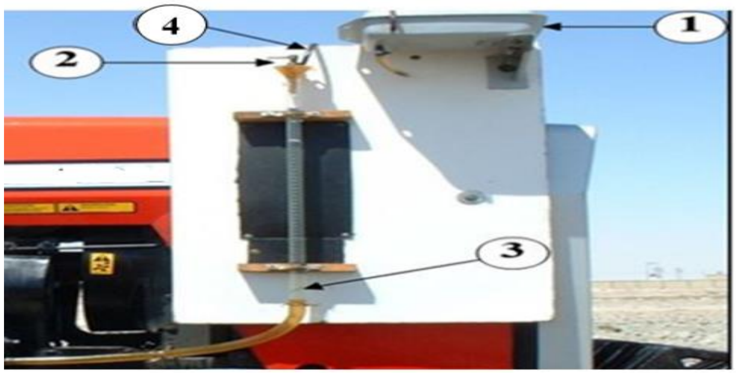

1- Fuel tank 2- Cone valve 3- Graduated cylinder 4-Excess fuel return pipe

Figure (3) Fuel consumption measuring device installed on the tractor.

Measuring fuel consumption rate

The fuel consumption rate of the Massey- Ferguson axtra 440 tractor was measured by determining a long distance of 20 m by installing two markers on the field ground with a distance of 20 m between them, then moving the tractor from a point far enough away from the first marker to stabilize the depth of the plow in the soil and for the tractor to reach the specified speed. When the center of the front tire of the tractor passes next to the first marker, the fuel level in the graduated cylinder is read at this moment, and then the fuel level in the graduated cylinder is read again when the center of the front tire passes opposite the second marker, and thus the difference between the two readings or fuel levels in the graduated cylinder is the amount of fuel consumed by the Massey- Ferguson axtra 440 tractor during the distance of 20 m. The average time required to cover the mentioned distance was also recorded. The fuel consumption rate was measured for all plowing parameters and the speed used with three repetitions. The fuel consumption rate was calculated from Equation 2 taken by Mettke et al. (1981).

$$Fcr = \frac{FC * 10}{Bp * va} \qquad (2)$$

Where: Fcr: Fuel consumption rate (L h^{-1}), FC: Fuel consumption rate (L h^{-1}), Bp: Working width of the tiller (m), Va: Operational speed (km h^{-1}).

Slip percentage

The slip percentage of the Massey- Ferguson axtra 440 tractor was calculated from equation 15 mentioned in Zoz and Grisso (2003). The practical forward speed was measured by calculating the average time taken by the tractor to cover a distance of 20 m during the plowing process. The theoretical speed of the tractor was also measured by calculating the average time taken by the tractor to cover a distance of 20 m on paved ground. The measurement process was repeated three times for all plowing parameters and forward speeds used in the experiment.

$$S = 1 - \frac{Va}{Vt} * 100 \qquad (3)$$

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Where: S: Slip percentage (%), Va: Practical speed (km h^{-1}), Vt: Theoretical speed (km h^{-1}).

Experimental design

The experimental field was divided according to the complete randomized block design and the split-split panel method was used in a factorial experiment with three factors (2 types of moldboard * 3 addition of rigid harrow * 3 forward speed) and with three replications where the moldboard type factor was put in the main plots and the addition of rigid harrow factor in the subplots, and the forward speed factor in sub-sub plots. The treatments were distributed randomly in the sectors, as the number of treatments reached (54) experimental units and the length of the experimental unit was 20 m. The data for all treatments were analyzed statistically using the statistical software Gen State Version 4. The means of the treatments were compared using the least significant difference test RLSD at a significance level of 0.05.

Results and Discussion:

Draft force

The results showed a significant effect of the types of moldboard on the drag force (Fig 4). The draft force increased with the use of finned moldboard. The finned moldboard (M2) recorded the highest value of drag force of 16.07 kN compared to the traditional moldboard (M1), which achieved the lowest value of draft force of 14.83 kN. This was attributed to the role of the fins of moldboard in intercepting soil blocks, which led to increased soil resistance to cutting and breaking up, thereby increasing the drag force compared to the plow with traditional moldboard. Also, the interception of the fins of the moldboard of the soil blocks, when it skids on the body of the moldboard results in increases in the surface area of contact of the soil masses with the inner surfaces of the plows thereby increasing the friction force between soil masses and finned moldboard body, which contributes to increasing the drag force. This is consistent with Alwan (2019), who noted that draft requirements for the moldboard plow differed according to the type of plow used and attributed this to the difference in the format of the moldboard and the area of contact with the soil masses.

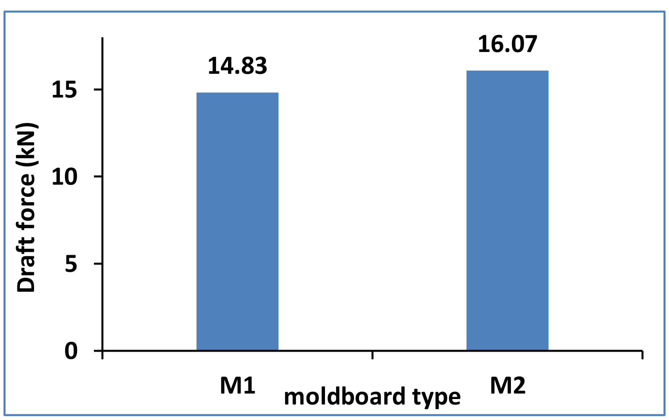

Figure (4): Effect of moldboard type on draft force (kN)

The results show a significant effect of adding a rigid harrow to the plow on the draft force (Fig. 5), the results showed an increase in the draft force of the plow with the addition of a rigid harrow. The highest draft force was recorded at 17.60 kN for double rigid harrows (H2) followed by single rigid harrow (H1) which achieved a draft force value of 15.73 kN. In comparison, the treatment without adding a rigid harrow to the plow (H0) recorded the

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lowest draft force value at 13.02 kN. The reason for the increase in the draft force of the plow with rigid harrows installed. This was attributed to the role of rigid harrows in increasing the loosening and smoothing of the soil masses plowed by the plow, which generates resistance from the soil masses to smoothing, and this increases the total force required for plowing and smoothing, thereby increasing the draft force compared to the pulling force of the plow alone. These results were consistent with what Muhsin (2017b) indicated, that using disc harrows after the chisel plow required an increase in the pulling force by 7.21 kN compared to using the chisel plow alone. Nassir et al. (2022) also confirmed that increasing the working parts in the compound tillage machine increases the pulling force requirements. They explained the reason for this by increasing the contact area between the working parts of the machine and the soil and increasing the soil resistance to tillage and loosening, which increases the required pulling force requirements.

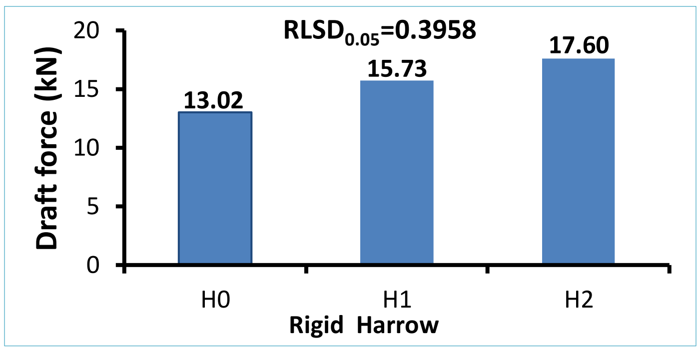

Figure (5): Effect of rigid harrow type on draft force (kN)

The results indicate a significant effect of forward speed on the pulling force. The results shown in Figure (6) showed that the pulling force increases from 14.04 to 15.46 and then 16.86 kN when the forward speed of plowing increases from 1.5 (S1) to 2.5 (S2) and then (S3) 3.5 km h^{-1}. The reason for the increase in draft force with the increase in forward speed is that the increase in speed leads to an increase in the energy required to move and accelerate the loose soil masses by the rototiller, which is reflected in the increase in draft force. These results are consistent with Damanauskas et al. (2019) and Abdollahpour (2023), who showed that increasing the practical speed of plowing increases the draft force requirements.

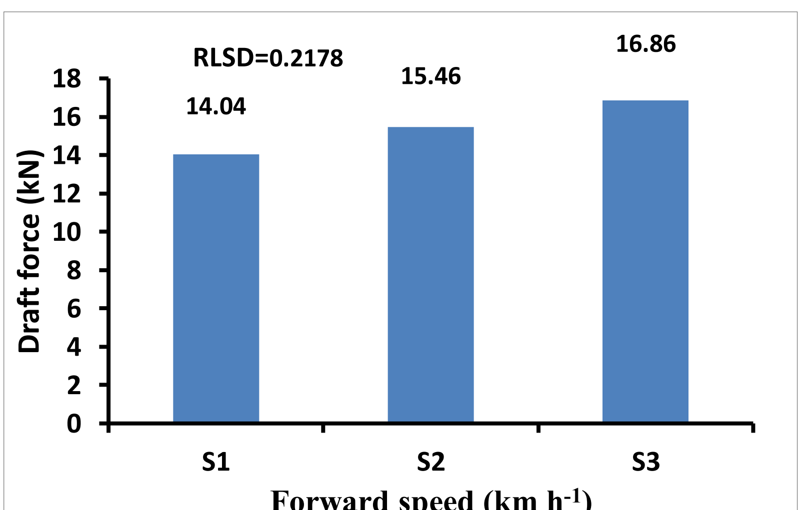

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Figure (6): Effect of forward speed on draft force (kN)

The results indicate that the interaction between the forward speed and the addition of rigid harrows significantly affected the draft force. The results in Figure (7) show that the highest pulling force was recorded for the interaction between forward speed (S3) and the addition of double harrows (H2) which reached 19.48 kN. In comparison, the lowest pulling force rate was recorded for the interaction between forward speed (S1) and plow treatment without the addition of rigid harrows (H0) reaching 11.40 kN. This is attributed to the combined role of both rigid harrows and the increase in forward speed in increasing the energy requirements required to loosen and accelerate the movement of the plowed soil masses compared to the traditional moldboard plow.

		Forward speed		
Moldboard types	**Rigid harrows**	**S1**	**S2**	**S3**
M1	**H0**	10.55	12.85	13.70
	H1	14.29	15.14	16.17
	H2	15.21	16.44	19.10
M2	**H0**	12.25	13.69	15.07
	H1	15.38	16.19	17.23
	H2	16.54	18.45	19.86
			RLSD=0.6329	

Figure (7): Effect of interaction between the forward speed and the addition of rigid harrows on draft force (kN)

The results show a significant effect of the interaction among the type of moldboard, the addition of rigid harrows, and the forward speed on the pulling force. The results in Table (2) show that the highest value of the pulling force was recorded for the interaction treatment between the finned plows and the double rigid harrows (H2) and the high forward speed (S3) reached 19.86 kN. In comparison, the lowest value of the pulling force was recorded when the interaction treatment was between the traditional plows (M1) and the treatment without adding rigid harrows (H0) and the low forward speed (S1) reached 10.55 kN. This is attributed to the combined effect of both adding fins to the plow and adding rigid harrows in increasing the loosening and smoothing of the plowed soil by the plow, which increases the energy requirements required to loosen the soil, which in turn increases the pulling force. Also, increasing the forward speed increases the energy requirements to move and accelerate the soil masses, increasing the pulling force.

The statistical analysis showed no significant effect of the interactions between the type of moldboard and the addition of rigid harrows to the tiller plow and the binary interaction between the type of moldboard and the forward speed on the pulling force.

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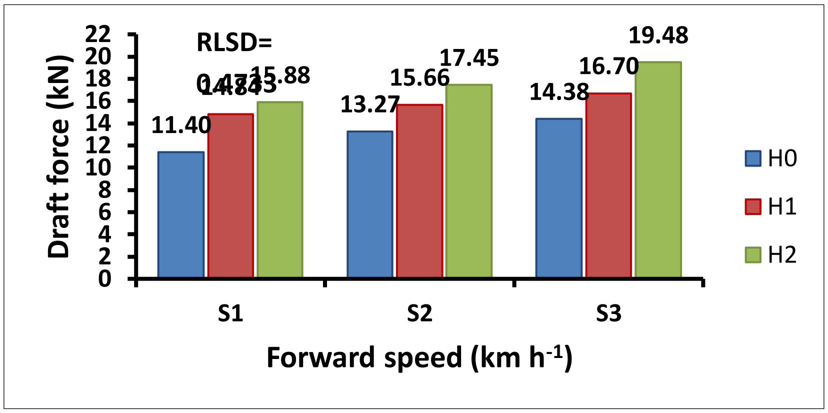

Slippage percentage (%)

The results showed a significant effect of the types of moldboard on the slippage percentage (Fig 8). The draft force increased with the use of finned moldboard. The finned moldboard (M2) recorded the highest slippage percentage value of 14.41% compared to the traditional moldboard (M1), which achieved the lowest slippage percentage value of 12.77%. This is attributed to the increased requirements of the pulling force of the plow with the finned moldboard to overcome the soil resistance to loosening, and this is reflected in the decrease in the practical speed of the plow, which leads to an increase in the slippage percentage compared to the plow with the traditional plow. Naif (2016) indicated that the increase in the energy requirements required for the plow in plowing and loosening the soil increases the slippage percentage as a result of the decrease in the practical speed of plowing. Talabani (2011) also found an increase in the percentage of slippage when adding fins to the moldboard of the plow. He attributed this to the fins increasing the fragmentation of soil blocks, which required greater pulling force and thus increased slippage.

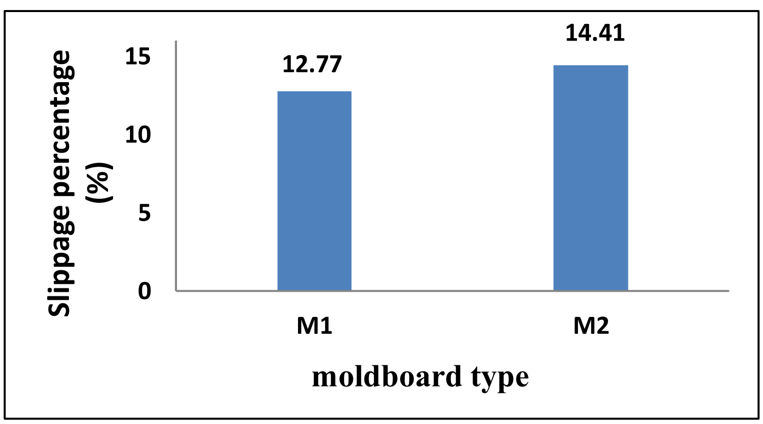

Figure (8): Effect of moldboard type on Slippage percentage (%)

The results show a significant effect of adding a rigid harrow to the plow on the percentage of slippage (Fig. 8). The results showed an increase in the percentage of slippage of the plow with the addition of a rigid harrow. The highest slippage percentage was recorded at 16.39% for double rigid harrows (H2) followed by single rigid harrows (H1), which achieved a slippage value percentage of 13.45%. Compared to treatment without adding a rigid harrow to the plow (H0), the lowest percentage of slippage was recorded at 10.95%. The reason for the increase in the percentage

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of slippage for the plow with the addition of double needle harrows is attributed to the increased resistance of the plowed soil to loosening and smoothing by the harrows and the increase in the required pulling force and the reduction in the practical speed of the plowing lead to an increase in the percentage of slippage. These results were consistent with what Al-Rahmani (2013) found, as he found that the percentage of slippage increases by 22.4% with the use of a combined machine consisting of a drill plow + disc harrows compared to a drill plow alone. Al-Khafaji (2020) also confirmed that the addition of smoothing equipment to the tillage machine as a single unit increases the percentage of slippage. He found that the percentage of slippage increases by approximately 17% for the plow with disc harrows added compared to the plow alone. He attributed this to the increase in the power requirements required for plowing and loosening the soil, which was reflected in the increase in the percentage of slippage.

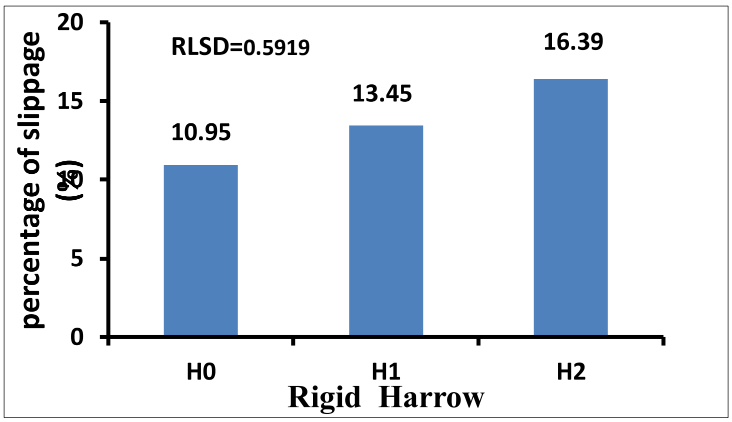

Figure (8): Effect of rigid harrow type on percentage of slippage (%)

The results indicate a significant effect of the forward speed on the percentage of slippage. The results shown in Figure (9) showed that the percentage of slippage increases from 11.82% to 13.57% and then 15.39% when the forward speed of plowing increases from 1.5 (S1) to 2.5 (S2) and then (S3) 3.5 km h^{-1}. This is attributed to the increase in the plow's requirements for traction force with the increase in forward speed in addition to the decrease in the period for the tractor wheels to contact with the soil surface, which is negatively reflected in the driving force and the decrease in the practical speed, thereby increasing the slip percentage. The results agreed with what Bovas et al. (2022) reached, as they noted that increasing the forward speed of plowing from 1.60 to 3.38 km h^{-1} led to an increase in the slip percentage by 27.39%.

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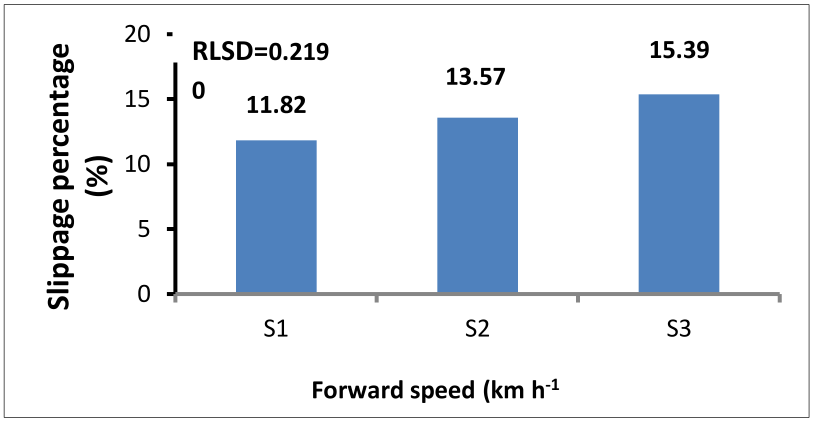

Figure (9): Effect of forward speed on Slippage percentage (%)

The results indicate that the interaction between the moldboard type and the forward speed significantly affects the percentage of slippage. Figure (10) showed that the highest slippage percentage was recorded for the interaction treatment between the moldboard with fins and the high forward speed of 3.5 km h^{-1} (M2*S3) amounted to 16.41%. The interaction between the traditional moldboard and the low forward speed (1.5) km h^{-1} (M1*S1) was recorded, as the lowest percentage of slippage value of 11.25%. This is attributed to the combined role of both increasing the forward speed and using the moldboard with fins in increasing the requirements of the traction force to overcome the soil resistance to dismantling, which is reflected in the decrease in the practical speed of the plow, thereby increasing the slippage percentage.

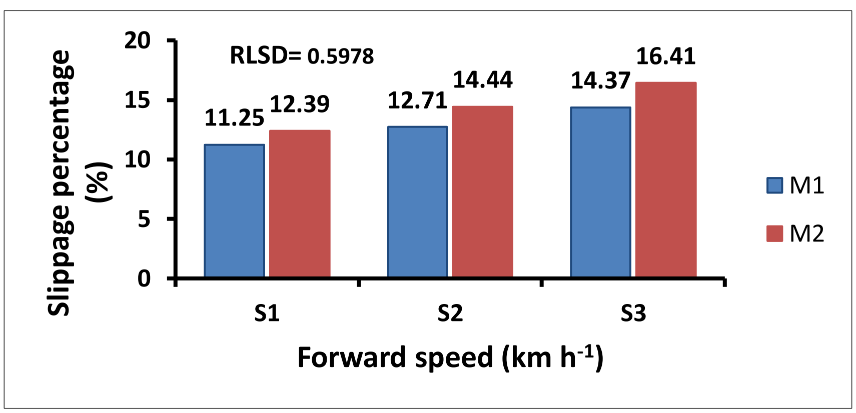

Figure (10): Effect of interaction between the moldboard with fins and forward speed on the percentage of slippage (%)

The results indicate that the interaction between the forward speed and the addition of rigid harrows significantly affected the percentage of slippage. The results in Figure (11) show that the highest percentage of slippage was recorded for the interaction between forward speed (S3) and the addition of double harrows (H2) which reached 18.42%. The lowest pulling force rate was recorded for the interaction between forward speed (S1) and plow

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treatment without adding rigid harrows (H0) reaching 9.14%. The reason for the increase in the percentage of slippage with the interaction treatment (H2*S3) is attributed to the role of increasing the forward speed in increasing the acceleration movement of the loosened soil masses, as well as the role of rigid harrows in increasing the smoothness of the plowed soil masses, which increases the requirements of the pulling force required to overcome the soil resistance to loosening led to decrease in the practical speed and thus the increase in the percentage of slippage, in contrast to the overlapping treatment (H0*S1) which achieved the lowest percentage of slippage due to the small number of working parts of the plow in the plowing process, in addition to the increase in the period required for cracks to occur in the soil with the decrease in the forward speed, which reduces the soil's resistance to disintegration and increases the practical speed, which in turn reduces the percentage of slippage.

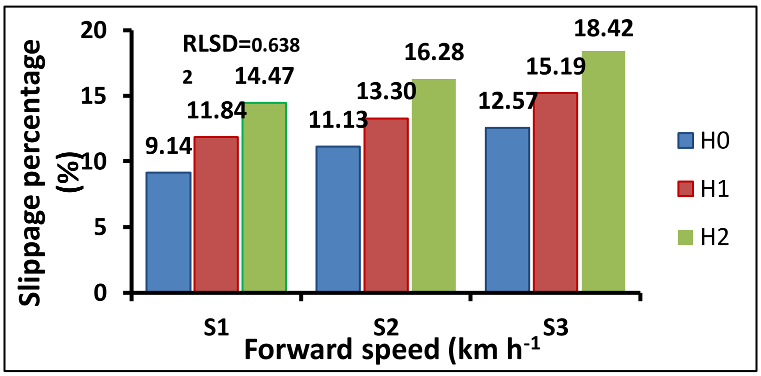

Figure (11): Effect of interaction between the rigid harrow and forward speed on the percentage of slippage (%)

The results show a significant effect of the interaction among the type of moldboard, the addition of rigid harrows, and the forward speed on the percentage of slippage. The results shown in Table (3) show that the interaction treatment (M2*H2*S3) achieved the highest slippage percentage value of 19.53%, while the interaction treatment (M1*H0*S1) recorded the lowest value of 8.2%. The reason for the increase in the percentage of slippage in the interaction treatment (M2*H2*S3) compared to other interaction treatments was attributed to the combined effect of each between type of moldboard with fins, the addition of a double rigid harrow, and the high forward speed in increasing the requirements of the pulling force required to overcome the soil resistance to loosening and smoothing, which reduced the practical speed of plowing, thereby increased the percentage of slippage. In contrast, the interaction treatment between (M1*H0*S1) excelled in achieving the lowest rate of slippage percentage due to the small number of working parts in the plow and the small number of working additives in the soil, in addition to the role of the low forward speed in providing a sufficient period for cracks to occur in the soil, which in turn reduces the soil resistance to loosening. And smoothing and then increasing the speed of the process, thereby reducing percentage of slippage.

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Fuel consumption rate

The results showed a significant effect of the types of moldboard on the fuel consumption rate (Fig 12). The fuel consumption rate increased with finned moldboard (M2) compared to the plow with traditional moldboard (M1) by 12.91%. The reason for the superiority of the traditional moldboard (M1) in achieving the lowest fuel consumption rate was attributed to the lower draft force requirements and the percentage of slippage, which reduced the amount of fuel consumed per unit area compared to the plow with the finned moldboard. Inthiyaz et al. (2020) and Almailiki et al. (2021) indicated that increasing the energy requirements and the percentage of slippage for the tillage machine increases fuel consumption.

Table 2. The effect of interaction among the type of moldboard, the addition of rigid harrows, and the forward speed on percentage of slippage (%).

		Forward speed		
Moldboard types	**Rigid harrows**	**S1**	**S2**	**S3**
	H0	11.42	12.37	13.37
M1	**H1**	14.12	15.45	17.29
	H2	10.07	11.97	12.69
	H0	12.26	14.24	17.02
M2	**H1**	14.82	17.11	19.54
	H2	11.42	12.37	13.37
		RLSD=0.8758		

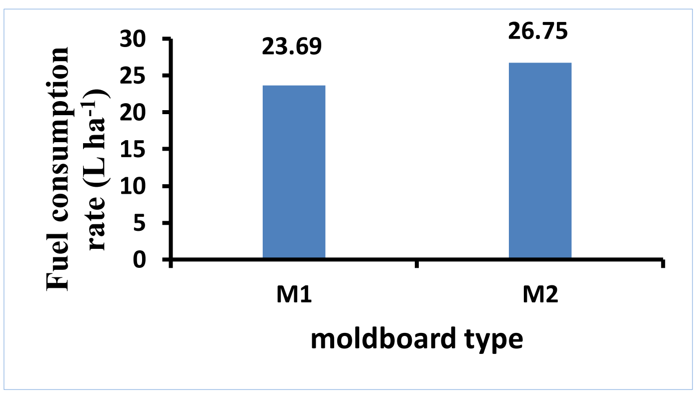

Figure (12): Effect of moldboard type on fuel consumption rate (L ha^{-1})

The results showed an increase significantly in the fuel consumption rate of the plow with the addition of a rigid harrow (Fig. 13). The highest fuel consumption rate was recorded at 29.10 L ha^{-1} for double rigid harrows (H2) followed by single rigid harrows (H1) which achieved a fuel consumption rate value of 125.29 L ha^{-1}. The treatment without adding a rigid harrow to the plow (H0) recorded the lowest fuel consumption rate of 21.27 L ha^{-1}. The reason for the superiority of the plow treatment without adding needle harrows (H0) in achieving the lowest fuel consumption rate compared to the rigid harrow adding was attributed to the superiority of the plow treatment alone in

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reducing the requirements of the pulling force and the percentage of slippage, consequently reduced the fuel consumption rate, These results were consistent with what Siddiq and Al-Gbadid (2019) reached, as they found that adding a smoothing tool to the chisel plow led to an increase in the fuel consumption rate by 13.05% compared to using the chisel plow alone. Nassir et al. (2022) also indicated an increase in the fuel consumption rate with the increase in the number of working parts in the compound tillage machine, and they attributed the reason for this to the increase in the capacity required for tillage and the increase in the time required to complete the work, which negatively affects the increase in fuel consumption per unit area.

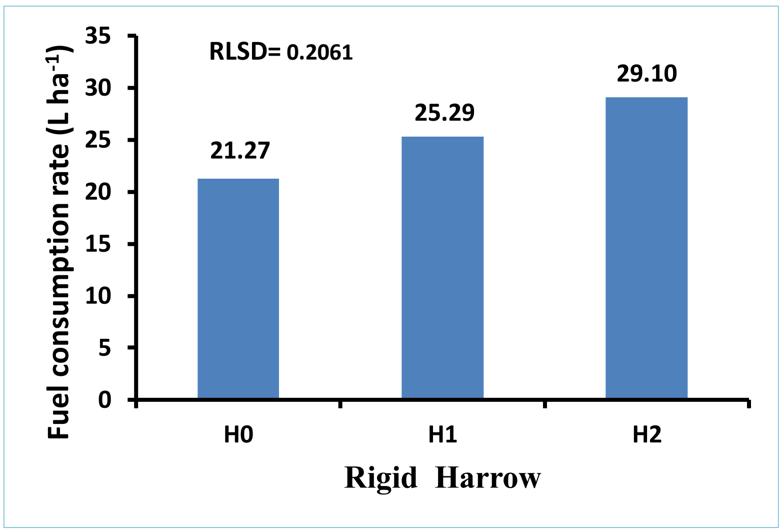

Figure (13): Effect of rigid harrow type on fuel consumption rate (L ha^{-1})

The results show a significant effect of forward speed on fuel consumption rate. It is noted from the results shown in Figure (14) that the fuel consumption rate decreased with increasing forward speed of plowing. The fuel consumption rate decreased from 31.65 to 23.86 and 20.16 L ha^{-1} with increasing speed from 1.5 (S1) to 2.5 (S2) and 3.5 (S3) km h^{-1}. The reason for the decrease in fuel consumption rate with increasing forward speed and the speed exceeding 3.5 km h^{-1} by achieving the lowest rate of fuel consumption was attributed to the fact that increasing the forward speed helps in optimal utilization of the tractor's capacity, reducing the period for plowing and increasing practical productivity, which reduced fuel consumption per unit area. These results were consistent with Al-Sharifi and Al-Jabouri (2011) and Xuanbin et al. (2019), who found a decrease in the fuel consumption rate with increasing forward speed and attributed this to the increase in the area of plowed soil per unit time, which was reflected in a decrease in the amount of fuel consumed per unit area.

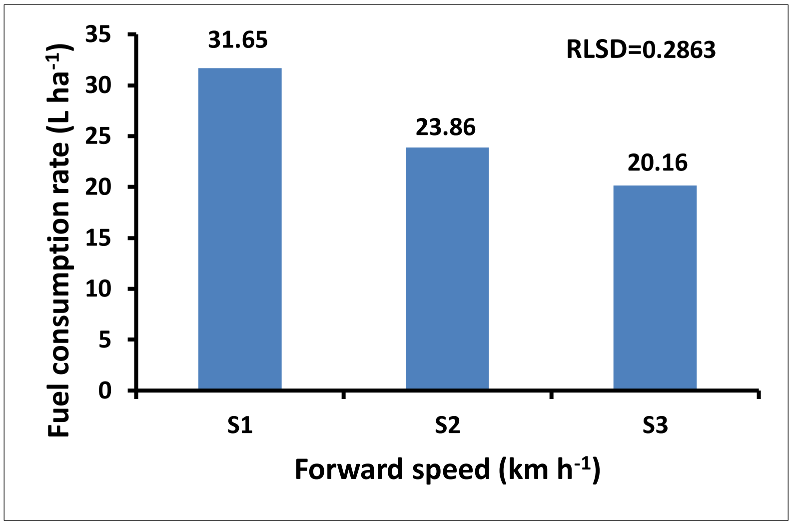

Figure (14): Effect of forward speed on fuel consumption rate (L ha^{-1})

The results indicate a significant effect of the interaction between the type of moldboard and the addition of rigid harrows to the plow on the fuel consumption rate. Figure (15) shows that the interaction treatment (M1*H0) is superior in achieving the lowest fuel consumption rate of 20.14 L ha^{-1}, while the interaction treatment (M2*H2) recorded the highest fuel consumption rate of 31.28 L ha^{-1}. The reason for the superiority of the interaction treatment (M1*H0) in achieving the lowest fuel consumption rate compared to other interaction treatments was attributed to the use of the traditional moldboard without adding rigid harrows, which reduced the requirements of the pulling force and the percentage of slippage consequently the decrease in the amount of fuel consumed per unit area.

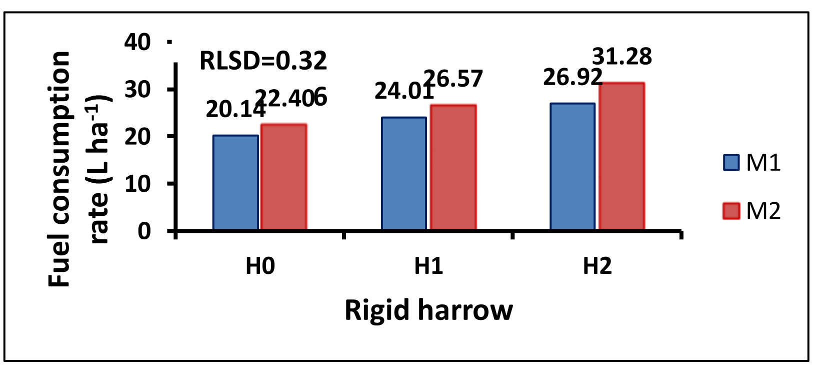

Figure (15): Effect of the interaction between the type of moldboard and the addition of rigid harrows on fuel consumption rate (L ha^{-1})

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Figure (16) shows that the rate of fuel consumption increased significantly with the addition of rigid harrows to the plow and the forward speed of the plow decreased. It is also noted that the highest fuel consumption rate was recorded for the interaction treatment between the low forward speed of 1.5 km h^{-1} (S1) and the addition of double rigid harrows to the plow (H2), which amounted to 35.37 L ha^{-1}. The interaction treatment between the high forward speed of 3.5 km h^{-1} (S3) and the plow without the addition of rigid harrows (H0) achieved the lowest fuel consumption rate of 16.60 L ha^{-1}. The reason for the superiority of the interaction treatment (H2*S1) in achieving the highest fuel consumption was attributed to the combined role of both the addition of a double rigid harrow leading to increased energy requirements required to loosen and pulverization of the soil causing an increase in the percentage of slippage. Also, the speed of 1.5 km h^{-1} increased the time required for plowing, thus decreasing practical productivity, which increased the amount of fuel consumed per unit area.

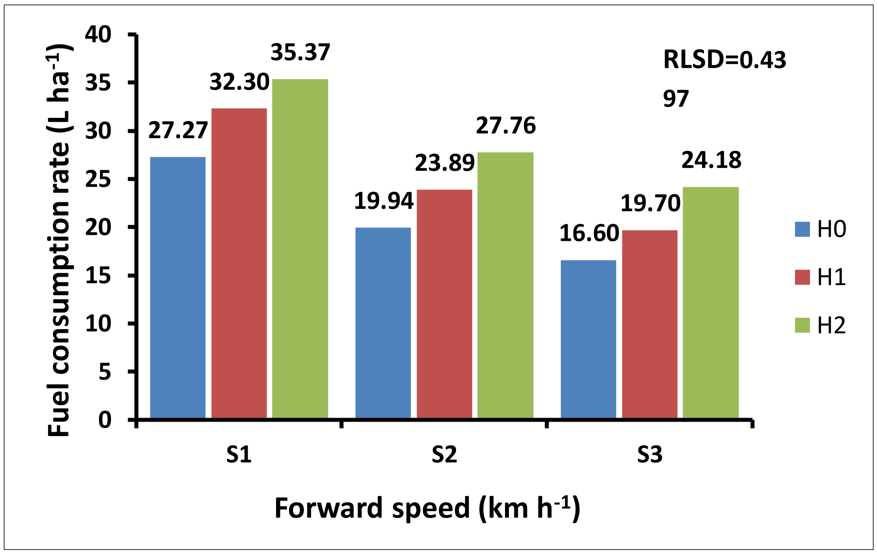

Figure (16): Effect of the interaction between the type of rigid harrows and forward speed on fuel consumption rate (L ha^{-1})

The results indicate that the interaction between the moldboard type and the forward speed significantly affects the fuel consumption rate. Figure (17) showed that the highest fuel consumption rate was recorded for the interaction treatment between the moldboard with fins and the high forward 33.20 L ha^{-1}. The interaction between the traditional moldboard and speed of 3.5 km h^{-1} (M2*S1) amounted to the low forward speed (1.5) km h^{-1} (M1*S3) was recorded, as the lowest fuel consumption rate value of 18.89. The reason for the decrease in fuel consumption rate in the interaction treatment (M1*S3) compared to other interaction treatments is attributed to the combined effect of increasing the forward speed, which decreased the time required for plowing per unit area, in addition to the decrease in the requirements of the pulling force and the percentage of slippage and the increase in the practical speed of plowing, thereby reduced the amount of fuel consumed per unit area, while increasing the period with the low-speed km h^{-1} and increasing the energy requirements and percentage of slippage for the plow with fins were reflected in the increase in the fuel consumption rate in the interaction treatment (M2*S1).

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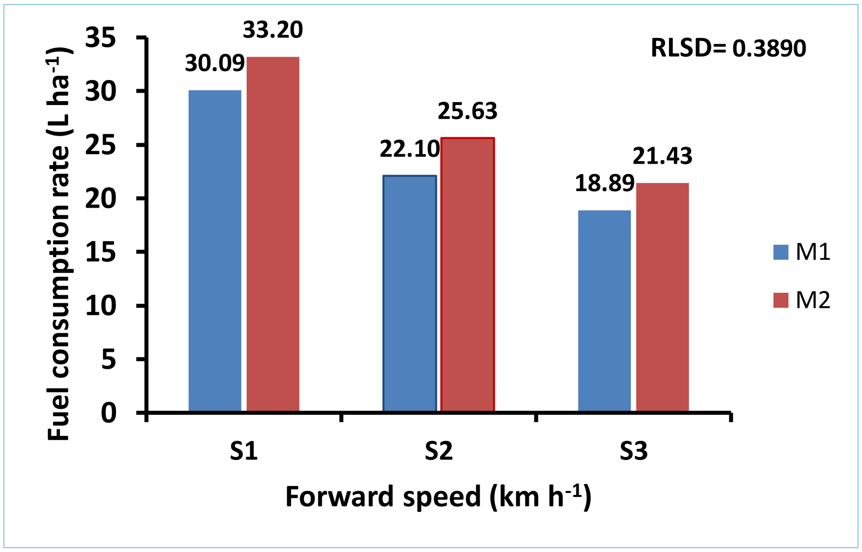

Figure (17): Effect of the interaction between the type of moldboard and the addition of forward speed on fuel consumption rate (L ha^{-1})

The results also show no significant effect of the interaction among the type of moldboard, the addition of rigid harrows to the plow, and the forward speed of tillage on the fuel consumption rate.

II. Conclusion

It can be conclusions the following from the Study:

The study demonstrated that the modified moldboard plow with finned moldboards (M2) achieves higher draft force, with an increase of 16.07 kN compared to 14.83 kN for the conventional plow. The results indicated that adding double rigid harrows (H2) to the plow increases draft force and slippage percentage, recording 17.60 kN for draft force and 16.39% for slippage, compared to the plow without harrows. The findings revealed that increasing forward speed leads to higher draft force and slippage percentage but reduces fuel consumption per unit area. The highest draft force was recorded at a speed of 3.5 km h^{-1} (16.86 kN), while fuel consumption decreased to 20.16L ha^{-1}. The study showed that the interaction between moldboard type, rigid harrow addition, and forward speed significantly affects performance. The highest values were achieved using finned moldboards with double rigid harrows at high speeds, recording a draft force of 19.86 kN.

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