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EVALUATION OF TRACTOR FUEL CONSUMPTION USING DIFFERENT TYPES OF PARAPLOUGHS AND MOULDBOARD PLOUGH

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Most of tillage research focuses on designing more efficient tools to operate with low energy consumption. Also, developing tools to preserve conservation tillage is a priority for researchers. The aim of the study was to compare a paraplough with and without wings with conventional mouldboard plough in terms of loosened area, fuel consumption, and specific fuel consumption. Field trials were conducted using an MF 285 tractor at three working depths of 10, 20, and 30 cm and at three forward speeds of 2, 5, and 7 km·h^{-1} for conventional mouldboard plough, paraplough without wings, paraplough with backward-bent wings, and paraplough with forward-bent wings. Two flow sensors made by Oval Company in Japan were used to measure the fuel consumption of the tractor. The highest fuel consumption of 14.58 L·h^{-1} occurred when using the mouldboard plough and the least fuel consumption of 5.849 L·h^{-1} was obtained using the paraplough without wings. Increasing travel speed and working depth increased fuel consumption significantly. Adding both backward- and forward-bent wings to the paraplough increased the loosened area by 17.25 and 7.4%, respectively. Also, adding wings increased specific fuel consumption by 54 and 74% in comparison with the paraplough without wings. Both loosened area and specific fuel consumption parameters showed using the backward-bent wing is more effective than the forward-bent wing in terms of energy efficiency. Using the backward- and forward-bent wings decreased specific fuel consumption by 34.1 and 18.7% in comparison with the mouldboard plough, respectively. It was concluded that for soil loosening using tines with wings is more effective in terms of energy saving.

Keywords: paraplough; wing; fuel consumption; soil

As the population and the demand for food increases, the need to plan for enough food supply has become more urgent than ever. The issue of sustainable agriculture has received much research in the last two decades. One of the key factors in sustainable crop production is the type of tillage used and the amount of energy it consumes (Tabatabaeefar et al., 2009; Mihov and Melnic, 2025). Tillage is the mechanical operation in the soil to prepare the land for cultivation. The purpose of proper tillage is to create a suitable bed for seed germination and to control soil moisture and soil erosion. Tillage is defined as the process of applying force to the soil to change its physical conditions and to disturb the soil surface to achieve the goals of softening the soil to prepare the seedbed, changing the soil topology, and mixing the soil with other materials. Tillage operations have a direct impact on the physical properties of the soil; therefore, selecting the appropriate method and executing it properly is crucial in shaping these properties (Wuest et al., 2006). Because of its significant influence on the soil's physical properties, tillage is regarded as one of the fundamental field operations in agriculture. Its main purpose is to create favourable conditions for plant growth and to enhance crop yield (Boydas and Turgut, 2007).

The most common, oldest, and at the same time the most important tillage tool is the mouldboard plough. It is suitable for ploughing various soils as a primary tillage implement used to cut, lift, overturn, and pulverise the soil and bury the surface plant residues (Kepner et al., 1978). Despite all the recommendation and advantage of conservation tillage, the use of mouldboard plough has been increased. From 2002 to 2017, the number of mouldboard ploughs in Iran has increased from 230,000 to about 350,000, which indicates convention tillage using primary tillage tools like mouldboard plough is widely practiced in developing countries (Nazemosadat et al., 2022).

Along with the mouldboard plough, a paraplough is also one of the new tools that has been developed to reduce the traction resistance of the paraplough operation. The paraplough consists of a shank and a diagonal blade. Attachments such as a shoe and a wedge tip are also attached to the end of the blade. In order to reduce the power required for paraplough operation and to reduce the cost of tillage operations, the effect of using the paraplough with wings and the mouldboard plough should be studied under different working conditions and compared, and the most optimal possible mode in the design of this type of tool should be presented in terms of energy consumption, soil mixing, plant residue burial, and furrow bed compaction (Al-Janobi, 2000). Due to the lack of rainfall and water resources in semiarid areas, in order to maintain soil moisture, especially in drought conditions, it is necessary to move towards tillage methods that leave a higher percentage of plant residues on the soil surface (Abbaspour Gilandeh et al., 2022). Conservation tillage is a method of leaving enough amount of crop residue on the surface of the field after harvest to increase soil protection from erosion. In this method, it is usually very important to reduce the amount of machinery and equipment traffic or to eliminate intensive tillage operations such as overturning the topsoil. The retention of crop residue on the soil surface is a characteristic that distinguishes conservation tillage from conventional methods. All conservation tillage systems maintain crop residue to cover at least 30% of the field surface (Abbaspour Gilandeh et al., 2022). In addition to the effort to perform the tillage operations correctly, optimising the agricultural operations and the tools used for this purpose is also of great importance. The tractor is the most important source of mechanical power generation for agricultural operations. The first purpose of using tractors in agriculture is to pull agricultural tools. The incorrect combination of tractor and agricultural tools is the most important factor in increasing fuel consumption and energy loss. Then, measuring and evaluating the performance parameters of the tractor and the tools connected to it is a great effort. In this regard, measuring the required tractive force of tools and providing models for predicting their required tractive force have attracted the most attention in field trials (Kheiralla et al., 2003).

The energy required for tillage accounts for a significant portion of the energy consumed in the production of agricultural products, and reducing this energy consumption has become a challenge for researchers and farmers. The main goal in improving tillage operations is to reduce energy consumption while achieving optimal soil conditions. The high cost of equipment and high energy consumption in tillage indicate the need to improve conditions in tillage operations. On the other hand, given the increasing cost of fuel in the world and awareness of the adverse effects of excessive tractor traffic in fields during seedbed preparation, the need to correctly select effective equipment and parameters to reduce draft force and increase soil loosening efficiency is increasingly felt. Tillage and the preparation of a suitable seedbed are among the most critical stages in the production of agricultural crops (Salar et al., 2013; Čėsna et al., 2022). Adewoyin and Ajav (2013) conducted a study to investigate the effects of tractor type, working depth, and forward speed on fuel consumption when using a mouldboard plough. Experiments were conducted using three types of tractors, Massey Ferguson (MF435), Fiat (F130D), and Steyr (CVT170) at three working depths of 20, 25, and 35 cm and three forward speeds of 5.5, 6.5, and 7.5 km.h-1. The results showed that the fuel consumption for different tractors, under the same working conditions, is significantly different. Also, increasing the working depth and forward speed caused a significant increase in fuel consumption. The most suitable mode for ploughing performance parameters in this study, considering the fuel consumption, was using a Fiat tractor with a forward speed of 5.6 km·h^{-1} and a working depth of 25 cm. Karparvarfard and Rahmanian-Koushkaki (2015) investigated the fuel consumption of a chisel plough using an ITM-399 tractor and a 9-tine chisel plough. Tests were conducted in loamy clay soil with a moisture content of 38.8%. In this test, the effective parameters for measuring fuel consumption included three working depths of 10, 15, and 20 cm, three forward speeds of 3, 4, and 5 km·h^{-1}, and two ploughshare widths of 5 and 10 cm. The results showed that increasing the working depth, forward speed, and ploughshare width of the plough increased fuel consumption.

Mouldboard plough is a prevalent tillage implement in developing countries. This research novelty is to investigate and indicate that the performance of the paraplough with wings is better than that of the mouldboard plough in terms of loosened area and energy saving. It tends to show that it is more beneficial to use the paraplough with wings instead of the mouldboard plough. The main objective of this research is to evaluate and compare the performance of the mouldboard plough, paraplough, and paraplough equipped with two types of wings at various working depths and forward speeds, focusing on fuel consumption. Based on fuel consumption, the suitability of using the paraplough with wings as an alternative to the mouldboard plough for conservation tillage in arid and semi-arid regions was evaluated.

Material and Methods

The trials were carried out at the research farm of Mohaghegh Ardabili University (48° 17″ 35′ E longitude, 38° 12″ 40′ N latitude, and 1350 m above sea level), where wheat residues from the previous cultivation remained on the soil surface. A 75 hp Massey Ferguson 285 single-drive axle tractor equipped with precision measuring instruments was used for this study. The measurement system consisted of a three-point linkage dynamometer, a fuel gauge, a fifth wheel mechanism, and a data acquisition system. A laptop connected to a data logger was used to record and collect data.

In this study, the hydrometric method was used to determine soil texture. The results of the experiment showed that the soil texture of the research field was loamy clay (Table 1). The experimental plot had a 4% slope. Field tests were conducted at three working depths of 10, 20, and 30 cm and at three forward speeds of 2, 5, and 7 km·h^{-1} for conventional mouldboard plough, paraplough without wings, paraplough with backward-bent wings, and paraplough with forward-bent wings (Fig. 1) (Askari et al., 2016), with five replications for each treatment. A total of 180 experiments were conducted using a randomised complete block design (RCBD). Each plot was 3 m wide and 15 m long.

The paraplough tines under investigation were of the standard type and their maximum working depth was 35 cm. The tines were made of a 25-mm thick steel sheet and weighed about 25 kg. The height and length of the branches at the top were 500 and 150 mm, respectively (Fig. 1). The leading angle of the lower part and the angle

Table 1 Soil analysis at the experimental site

Soil property	Value
Sand (0.02–2 mm)	41%
Silt (0.002–0.02 mm)	28%
Clay (< 0.002 mm)	31%
Organic carbon	0.29%
Electrical conductivity (EC)	0.41 ds·m^{-1}
Liquid limit	30%
Plastic limit	20.1%
Field capacity (ds)	25.13%
Dry bulk density (0–10 cm)	948 kg·m^{-3}
Dry bulk density (0–20 cm)	1004 kg·m^{-3}
Dry bulk density (0–30 cm)	1112 kg·m^{-3}
Moisture content (db) (0–10 cm)	7.76%
Moisture content (db) (0–20 cm)	11.24%
Moisture content (db) (0–30 cm)	18.46%

db – dry base

of deviation from the vertical line of the paraplough tine were 23.41 and 41.86°, respectively, and the inclination angle was 48.14°. The angle of attack (α) of the blade tip in the paraplough tine was also chosen to be 15°, which is the most optimal in terms of the required traction force (Fig. 2).

In order to measure fuel consumption, two methods are used – using sensors in the fuel transfer pipes and the tank-filling method. Using the tank-filling method is more desirable, considering that it does not require changes in the tractor fuel supply system (Clark and Adsit, 1985). However, the low accuracy of this method prevents its use in scientific research. For accurate and continuous measurement of fuel consumption, sensors are placed in the fuel return paths (Raper, 2002). To measure fuel consumption during each tillage operation, two OVAL M-III flow sensors (model LSF 40, Kamiochiai 3-chome, Shinjuku-Ku, measurement capacity of 2–100 L·h^{-1}, Tokyo, Japan) were used. One sensor was employed to measure the fuel entering the injection pump, while the second sensor measured the amount of fuel returning from the fuel

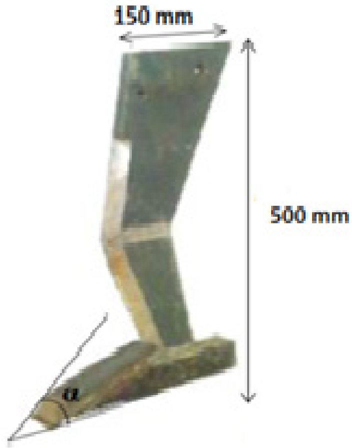

Fig. 2 Paraplough tine with a 15° angle of attack

circuit to the tank (Fig. 3). Both sensors were connected to an instantaneous fuel consumption indicator (model FM101-50, Iran). This indicator was then connected via another cable to the data acquisition system.

In order to measure the forces exerted by the soil on the implements, a three-point linkage dynamometer was used (Fig. 4). The aforementioned dynamometer was capable of measuring the horizontal, vertical, and lateral forces applied to the blades of both the paraplough and the mouldboard plough, which was designed by Abbaspour-Gilandeh and Khan-Ramaki (2013). It can measure draft force up to a maximum value of 20 kN, as well as the torques generated around the coordinate axes up to a maximum of 20 kN·m. The force measurement unit consists of two ring-type force transducers with an octagonal structure, which are connected back-to-back at a 90° angle by means of intermediate rings, and a tubular torque transducer that was attached to one of these force transducers. The octagonal ring transducers measure the three components of force and the bending moments acting on them, while the tubular torque transducer measures the torsional torque applied to the measurement unit. The output signals from the strain gauges were first recorded in a data logger (DT-800, Data taker Australia, High-speed general-purpose data logger, 16 digital channels and 12 analogue channels, operated with 220 V current,

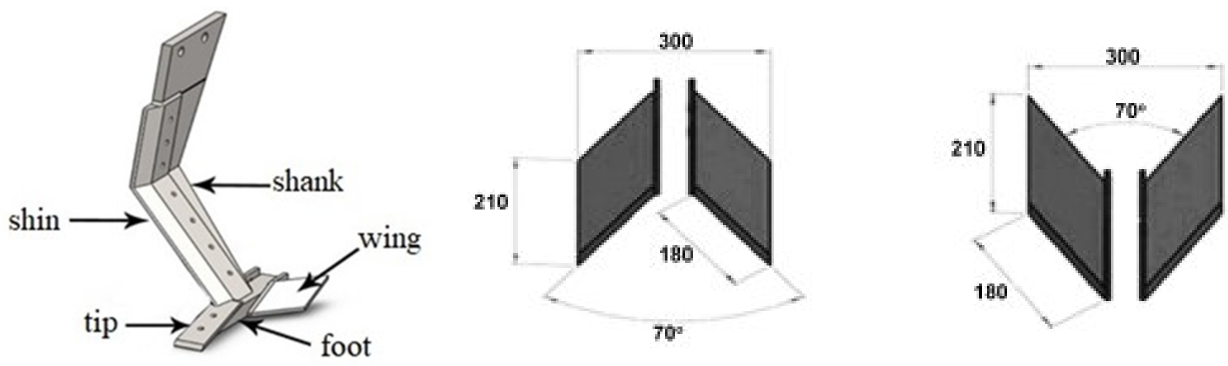

Fig. 1 a – components of a paraplough tine; b – forward-bent wing dimensions; c – backward-bent wing dimensions

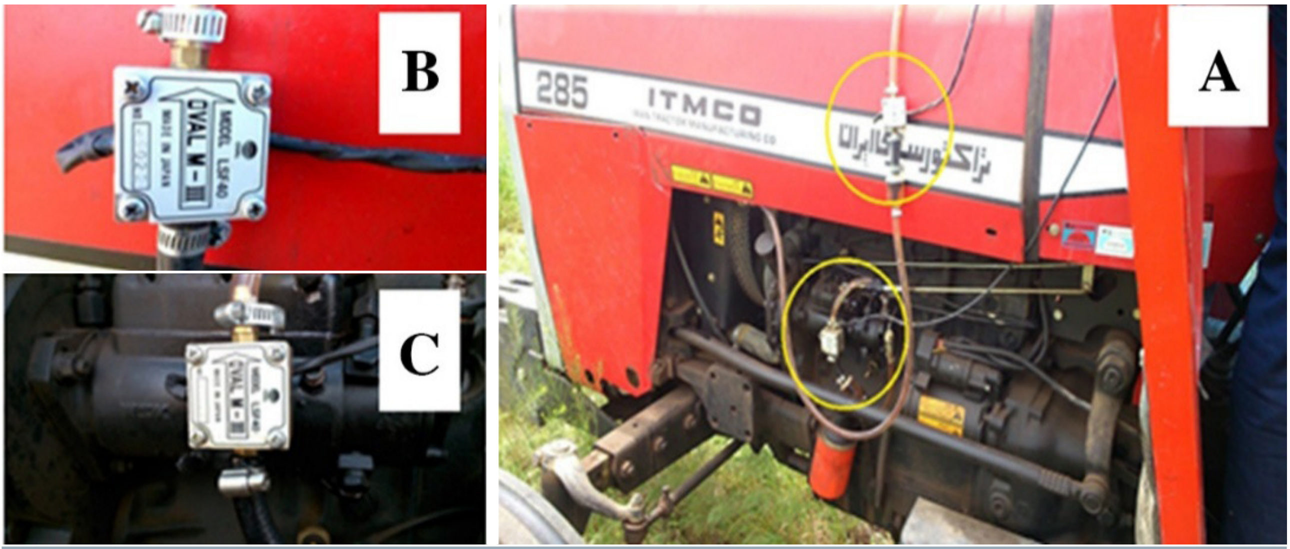

Fig. 3 Real-time measurement of tractor fuel consumption using flow sensors
A – overview; B – sensor installed on the return path; C – sensor installed on the forward path

16-bit resolution, and the maximum hardware sampling speed of 100 kHz) and then transferred to the laptop (Dell, Core i5, 12 GB RAM, and 1 TB SSD) for storage. The data logger used was programmable and capable of recording various types of input data. A sampling frequency of 20 Hz (20 readings per second) was selected for the data logger. The data logger, laptop, and digital display of the fuel measurement system were located inside the tractor cabin near the driver, and their energy requirements were supplied through a 12 V direct to 240 V alternating current converter connected to an additional battery (Fig. 4). The statistical analysis of the obtained data was performed using SPSS 26 software.

Results and Discussion

The results of the analysis of variance of all investigated factors on fuel consumption are presented in Table 2. Data were analysed using a factorial design within a completely randomised design framework, employing SPSS version 26 software. According to the analysis of variance results, all

Fig. 4 Three-point-hitch dynamometer and data acquisition system inside the tractor cabin

Table 2 Analysis of variance (ANOVA) of the effect of investigated parameters in the tractor fuel consumption

Source of variation	Degree of freedom	Sum of square	Mean square	*F*-value
Tillage tool	3	1362.24	454.1	139553.75**
Speed	2	341.01	170.5	524.02**
Depth	2	110.62	53.3	16999.02**
Tool*speed	6	29.31	4.88	15101.44**
Tool*depth	6	2.74	0.45	140.23**
Speed*depth	4	3.24	0.81	249.15**
Tool*speed*depth	12	2.81	0.23	72.11**
Error	144	0.469	0.003	
Total	180	19645.19		

** highly significant ($P < 1\%$)

main factors as well as two-way and three-way interaction effects were statistically significant at the 1% probability level.

Effect of implement type, velocity, and depth on fuel consumption

Figure 5a shows the effect of tillage implements type on fuel consumption. The highest fuel consumption of 14.58 L·h^{-1} occurred when the mouldboard plough was used. The lowest fuel consumption of 5.849 L·h^{-1} was achieved by the paraplough without wings. The fuel consumption of the paraplough with backward-bent wings was 9.886 L·h^{-1}, which was less than in the paraplough with forward-bent wings (10.449 L·h^{-1}). As is clear from the graph, the type of tillage implement will affect fuel consumption, which is in accordance with the opinion of Kheiralla et al. (2003). Abbaspour-Gilandeh et al. (2020) showed that the traction force of the paraplough with backward-bent wings was lower than that of the paraplough with forward-bent wings at all speeds and working depths, which was expected due to the shape of the blades and the increased soil contact of the forward-bent wings on the paraplough tine. Figure 5b shows the effect of forward speed on fuel consumption. With increasing forward speed, fuel consumption increased significantly, which is in accordance with the research of Karparvarfard and Rahmanian-Koushkaki (2015). The highest fuel consumption of 11.51 L·h^{-1} occurred at a speed of 7 km·h^{-1}, and the lowest fuel consumption of 8.16 L·h^{-1} was recorded at a speed of 2 km·h^{-1}.

Figure 5c shows the effect of working depth on fuel consumption. Fuel consumption increased significantly with depth increase. The minimum fuel consumption of 8.7 L·h^{-1} was recorded at a working depth of 10 cm, whereas at 30 cm, it increased to 10.9 L·h^{-1}, demonstrating approximately 61% higher fuel usage at the greater depth. Karparvarfard and Rahmanian-Koushkaki (2015) reported similar results.

Figure 6 illustrates the interaction effect between the type of tillage implement and different forward speeds on fuel consumption during the tillage operation. The highest fuel consumption of 15.8 L·h^{-1} was observed when using the mouldboard plough at a forward speed of 7 km·h^{-1}, whereas the lowest fuel consumption of 4.49 L·h^{-1} was recorded with the paraplough without

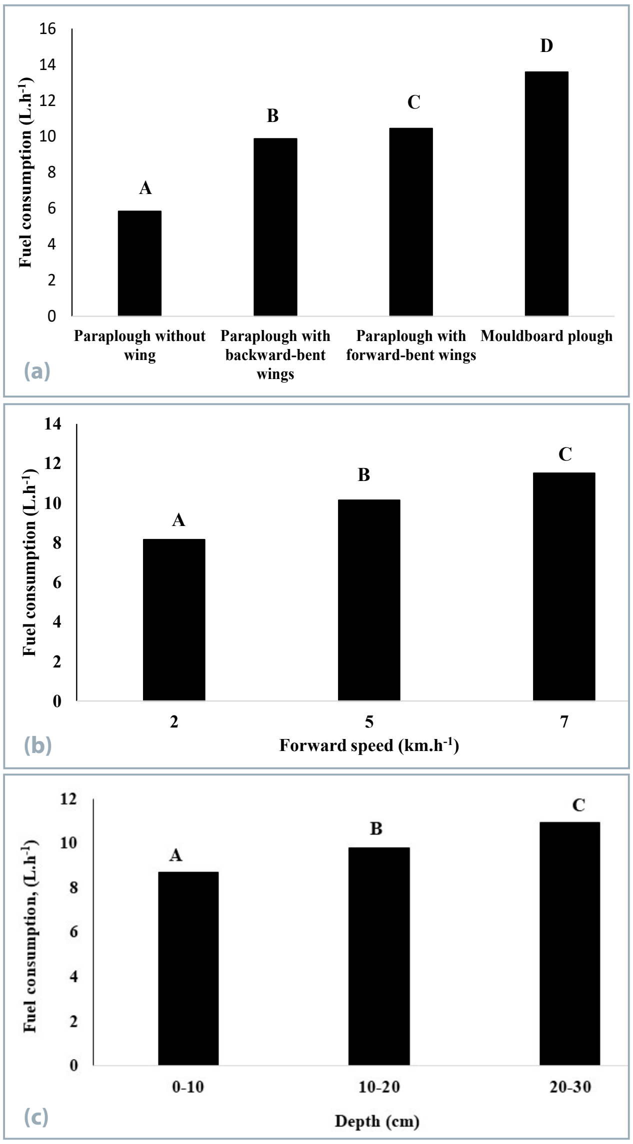

Fig. 5 a) The effect of tillage tool on fuel consummation; b) and c) The effect of tillage speed and working depth on fuel consumption

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wings at a low forward speed of 2 km·h^{-1}. In general, it can be said that in all implements, fuel consumption increased with increasing forward speed. Therefore, in order to achieve the desired fuel consumption, primary tillage operations which require high fuel consumption should be carried out at a relatively low range of standard speeds. Comparing tine fuel consumption showed that adding wing to the paraplough tine increased fuel consumption, which is in accordance with Salar et al. (2013).

Table 3 presents the fuel consumption values for four different ploughs at various speeds. It shows that the paraplough had the lowest fuel consumption across all speeds, while the mouldboard plough recorded the highest values. Both paraploughs with backward-bent and forward-bent wings showed similar consumption levels, with values falling between those of the standard paraplough and the mouldboard plough.

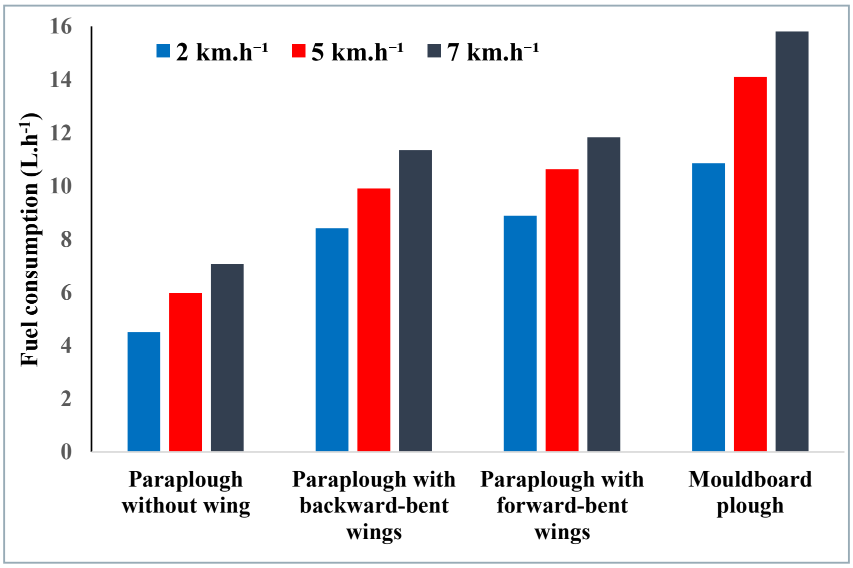

Fig. 6 Mutual effect of tine type and forward speed on fuel consumption

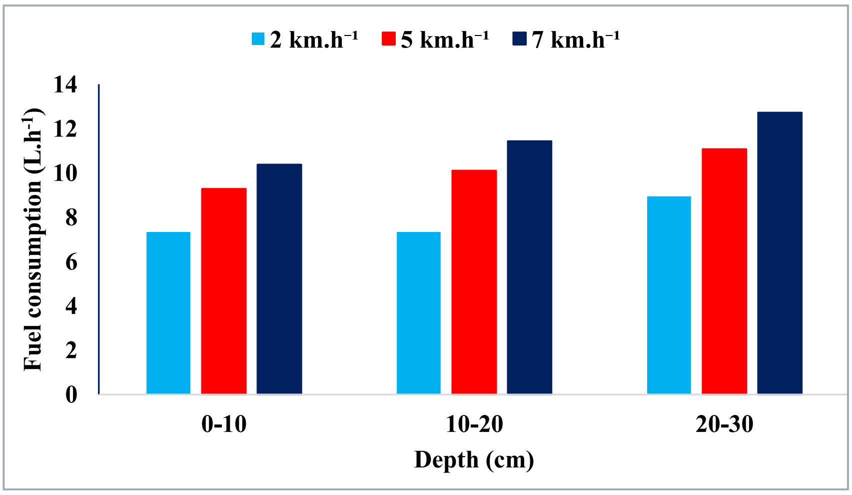

Fig. 7 Interaction effect of working depth and forward speed on fuel consumption

Figure 7 shows the interaction effect of forward speed at different levels of working depth on fuel consumption during tillage operations. The highest fuel consumption (12.37 L·h^{-1}) was recorded at a depth of 30 cm and a forward speed of 7 km·h^{-1}, while the lowest fuel consumption occurred at a shallow depth of 10 cm and a low speed of 2 km·h^{-1}. The results showed that fuel consumption increased with increasing working depth and forward speed, which is consistent with the research of Kheiralla et al. (2003) and Karparvarfard and Rahmanian-Koushkaki (2015).

Figure 8 presents the three-way interaction effect of tillage implement type, forward speed, and working depth on tractor fuel consumption. The highest fuel consumption of 17.08 L·h^{-1} was recorded with the mouldboard plough at a forward speed of 7 km·h^{-1} and a depth of 30 cm, while the least fuel consumption of 3.93 L·h^{-1} was obtained with the paraplough without wings at a forward speed of 2 km·h^{-1} and a depth of 10 cm. In general, in all tillage implements, a significant increase in tractor fuel consumption was observed with increasing working depth and forward speed, which is consistent with the findings of Askari et al. (2016). Chenarbon (2022) showed that the maximum fuel consumption of 68.67 L·h^{-1} and the minimum fuel consumption of 44.73 L·h^{-1} for the mouldboard plough were measured in the 10 and 30 cm tillage depths at the slippage values of 21.32% and 11.84%, respectively. Moreover, increasing tillage depth from 10 to 20 cm and from 10 to 30 cm increased fuel consumption by 18.90 and 53.52% due to increased soil volume and weight in higher tillage depths, requiring more cutting force.

Table 3 Fuel consumption values for different ploughs at different forward speeds

Forward speed (km·h^{-1})	Paraplough without wings (L·h^{-1})	Paraplough with backward-bent wings (L·h^{-1})	Paraplough with forward-bent wings (L·h^{-1})	Mouldboard plough (L·h^{-1})
2	4.5	8.41	8.88	10.85
5	5.97	9.9	10.63	14.09
7	7.08	11.34	11.83	15.8

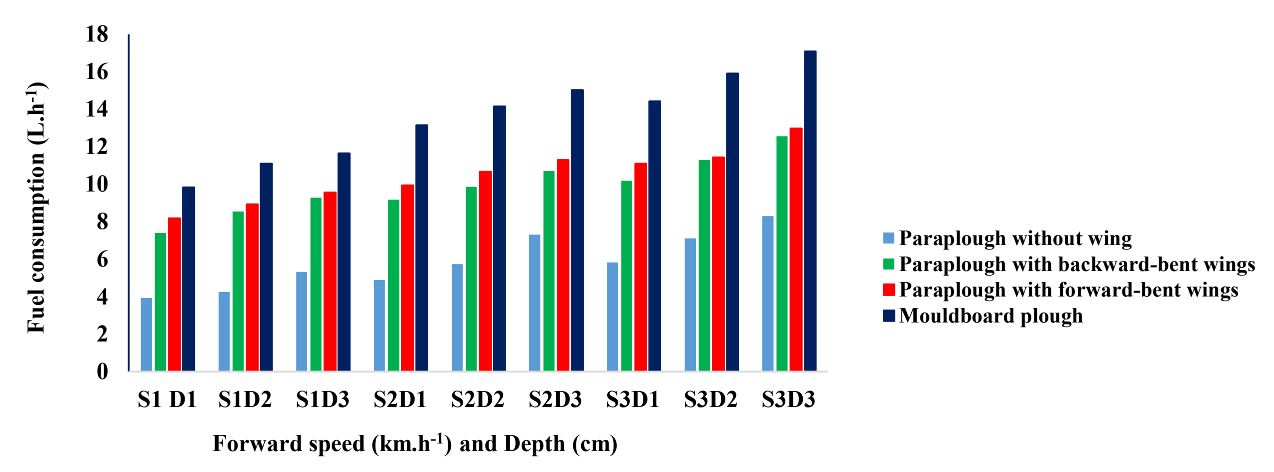

Fig. 8 Three-way interaction of tillage implement type, forward speed (S1 = 2, S2 = 5, S3 = 7 km·h^{-1}), and working depth (D1 = 10, D2 = 20, D3 = 30 cm) on fuel consumption

Effect of implement plough type on loosened area and specific fuel consumption

Figure 9a shows that the paraplough without wings loosened the area of 1280.2 cm^2, which was less than the other tines. Then, adding wings to the tine increases the loosened area. Tines with wings loosened the same area as the mouldboard plough. However, specific fuel consumption (SFC) showed that the paraplough without wings obtained the least SFC of 47.7 L·m-2. This indicates that although the tines without wings loosened less area, they also used the least fuel. Therefore, this tine is recommended for light tillage operations aimed at preserving conservation practices. Adding both backward- and forward-bent wings increased the loosened area by 17.25 and 7.4%, respectively. Figure 9b shows that adding the wing increased SFC by 54 and 74% in comparison with the paraplough without wings. Both loosened area and SFC parameters indicate that using backward-bent wings is more beneficial than forward-bent wings in terms of energy efficiency. The wings act like a wedge, causing soil failure to occur in shear instead of tension. Since soil is weak in shear, but highly resistant to compression (Askari et al., 2019). Askari et al. (2019) found that adding backward-bent and forward-bent wings to the tines increased their efficiency in comparison to the tine without wing and conventional wings in terms of loosened area and SFC. Adding both types of wings increased the loosened area while reducing fuel consumption in comparison to the mouldboard plough. Using backward- and forward-bent wings decreased the SFC by 34.1 and 18.7%, respectively, in comparison with the mouldboard plough. It was concluded that using tines with wings for soil loosening is more efficient in terms of energy saving.

Interaction effect of plough type and working depth on specific fuel consumption

Figure 10 shows the SFC of different ploughs at different depths. At a shallow depth of 10 cm, the SFC is very high for all ploughs, indicating that their use is not efficient at this depth. This indicates that mouldboard plough and paraploughs with wings, which tend to loosen a relatively large area, should be used at depths greater than 20 cm. As the depth increased from 10 to 20 and 30 cm, the SFC of the paraplough with forward-bent wings decreased by 73 and 95%, respectively. These decreases were 56 and 71% for the mouldboard plough. Further research at depths greater than 30 cm is required to determine the maximum depth at which the SFC continues to decrease.

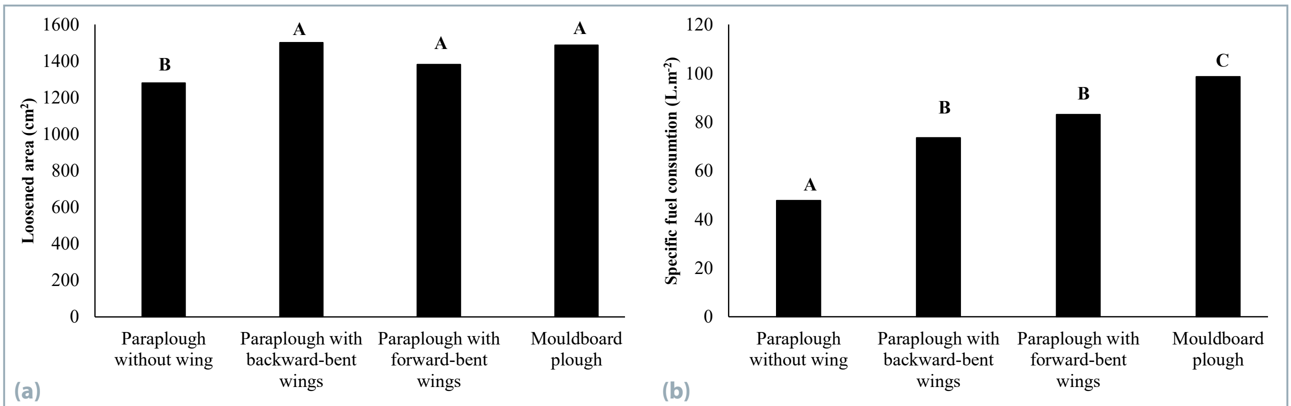

Fig. 9 a) Loosened area of different ploughs; b) Specific fuel consumption of different ploughs

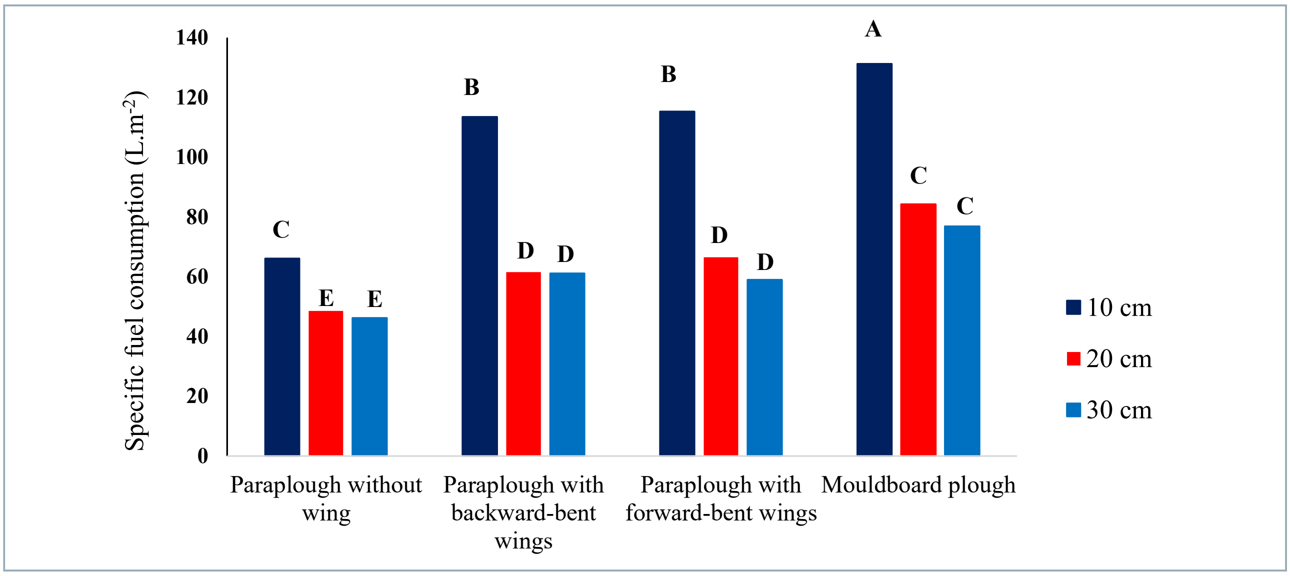

Fig. 10 Specific fuel consumption of different tines at different working depths

Conclusion

The results of this study demonstrate that tractor fuel consumption during tillage operations is strongly influenced by the type of implement, forward speed, and working depth, as well as by their interactions. Among the implements tested, the mouldboard plough consistently showed the highest fuel consumption, while the paraplough without wings was the most fuel-efficient. Increasing forward speed and working depth led to significant increases in fuel consumption across all implement types. Furthermore, the addition of wings to paraplough tines increased the loosened soil area but also affected specific fuel consumption, with tines with backward-bent wings generally exhibiting better energy efficiency than tines with forward-bent wings. These findings highlight the importance of selecting appropriate tillage implements and operating parameters to optimise fuel use and energy efficiency in agricultural operations. The main conclusions can be summarised as follows:

1. Specific fuel consumption (SFC): Comparing the paraploughs (with and without wings) to the mouldboard plough revealed that adding wing to the tine increased the loosened area and fuel consumption. SFC data indicate that the paraplough with wings is more efficient than the mouldboard plough. The use of backward- and forward-bent wings decreased the SFC by 34.1 and 18.7%, respectively, in comparison with the mouldboard plough.
2. For conservation tillage, the paraplough without wings is recommended due to its minimum soil disturbance and lowest fuel consumption. The lowest SFC of 47.7 L·m-2 was obtained using this plough. Its SFC was 106% lower than that of the mouldboard plough.
3. The study concluded that fuel consumption rises as forward speed and working depth increase across all tillage implement types. Therefore, to achieve the target fuel consumption, tillage operations should be carried out at the lower end of the standard speed range. SFC results indicated that the maximum efficiency for all ploughs is achieved at depths greater than 20 cm.

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