

Acta Technologica Agriculturae 1
Nitra, Slovaca Universitas Agriculturae Nitriae, 2025, pp. 32–40

COMPARISON OF SUBSOILER PLOW PERFORMANCE USING DIFFERENT VIBRATION WINGS DESIGNS

Hussein Alaa Aldin AL-AABAGH¹, Yousif Yakoub HILAL^{1*}, Karrar MAHDI²

¹University of Mosul, College of Agriculture and Forestry, Department of Agricultural Machines and Equipment, Mosul, Iraq, hussinalaa.22agp97@student.uomosul.edu.iq

²Wageningen University & Research, Soil Physics and Land Management Group, Wageningen, The Netherlands, karrar.mahdi@wur.nl

*correspondence: yousif.yakoub@uomosul.edu.iq

The study aims to manufacture and develop the vibrating wings for the subsoil plough and to evaluate the performance of the locally manufactured wings and their impact on the stability of the driver's seat, noise, slipping, and fuel consumption. Three factors were used to evaluate the performance of the subsoiler plough, the factors including the types of vibrating wings, traditional vibrating wings (TD35) and two designs of locally manufactured wings (ND35 and ND45), and two angles of penetration of 40° and 50° at a speed of wings vibration of 60 and 120 m·s⁻². The experiment was analysed using a randomised complete block design with a split-plot design and Duncan's multiple range test at the 0.05% and 0.01% probability levels. The results showed that the stability of the driver's seat and noise in TD35 was higher than that in both ND35 and ND45, with higher values of approximately 2.450 m·s⁻² and 86.4 dB. The vibration and noise values are considered higher than those specified by international organisations that protect farmers in agricultural work (European Parliament Directive 2003/10/EC). Moreover, ND35 recorded the lowest slipping and fuel consumption results, estimated at 7.948% and 4.563 l·h⁻¹ at the penetration angles of 50° and 40°, respectively. Finally, the results showed that the stability of the driver's seat, noise, slipping, and fuel consumption were higher at TD35; simultaneously, the best results were achieved as the solution for the problem when using ND35 in the 40° and 50° penetration angles with both wings vibrations. The conclusion is that local vibrating wing designs reduced all the characteristics studied.

Keywords: fuel consumption; noise; slipping; soil compaction; speed of wings

The entry of agricultural machinery and heavy equipment into the soil without following scientific methods has had positive and negative effects on certain soil features and plant growth. Plough machines and tillage techniques have influenced soil properties and plant growth (Francaviglia et al., 2023; Kalfas et al., 2024). The mechanisation of agricultural operations, intensive farming, and continuous use of agricultural machinery have led to soil compaction (Syromyatnikov et al., 2024; Mojžiš et al., 2024). The movement of tractors and consolidation in forming a compacted subsoil layer at a depth of 52 cm in the root zone restrict root growth and density. Reduced root growth and density decrease nutrient absorption and crop productivity (Sharma and Kumar, 2023).

In the studies conducted by Jebur (2023), Shahgholi et al. (2023), and Porto Ale et al. (2023) to investigate the impact of agricultural tractors and equipment on soil compaction, it was found that as depths increased, the penetration resistance and the surface density of the soil increased, while the total porosity of the soil decreased significantly. It is due to the increase in depths that soil resistance to external forces increases, and a more significant impact is on a larger soil volume and growing vertical forces by agricultural tractors and equipment. In clayey soil, Vanderhasselt et al. (2023) assessed the effect of soil compaction under the influence of different tillage systems; the average overall penetration resistance increased with depth, reaching 5.1 MPa.

Conventional and vibratory subsoiler ploughs lead to soil surface disintegration to a certain depth known as the critical depth. This disintegration is called a crescent failure, where the soil moves upward towards the surface, forward, and sideways, reducing its superficial density. The soil undergoes compressive failure below the critical depth, compacting it as its movement is forward and sideways. The combined effect of both processes is called the tilled soil area. This type of plough, especially vibratory ploughs, dramatically affects the stability of the driver's seat, noise, fuel consumption, and many other characteristics, positively or negatively (Askari et al., 2019; Li et al., 2022).

Tractor drivers are usually subjected to significant body vibrations during agricultural work because of various factors such as land topography and operators' seating position. High-intensity vibrations, like lower back pain, may result in operators' health sufferance. The vibrations of moving agricultural machinery reaching the operator's body through different points, including the tractor's steering wheel, seat, and lifting tools, can exceed the exposure value of 0.5 m·s⁻² (Cutini et al., 2017). The accelerations that affect human health are classified into linear and periodic acceleration groups. Linear vibrations transfer to three axes: vertical, longitudinal, and lateral, affecting both the instrument (tractor) and the human body. Longitudinal vibrations are more sensitive (i.e., having a higher impact than vertical vibrations) on tractor operator's health according to tractor's

condition (Shahgholi et al., 2019; Singh et al., 2023). As for many field experiments, tractor and loader operators are exposed to frequencies ranging from 5 Hz to 11 Hz (Abouel-seoud, 2019). Much factual evidence proves that agricultural tractor drivers often suffer from various cases, such as tissue injuries, joint pains, and abdominal discomfort. Concerning traditional tractors, the vibration acceleration is typically around $0.5\text{--}1.5\text{ m}\cdot\text{s}^{-2}$, with a vibration frequency range of approximately 2–7 Hz (Zeng, 2016; Singh et al., 2023).

Fuel consumption and noise depend on the power of drawing, speed of an engine, anterior speed of the tractor, designs, width, depth of the agricultural equipment, and the type of soil and its involved humidity. Fuel consumption is the amount of fuel consumed for tillage and other fieldwork. In addition, increasing the depth level in farm works leads to a decrease in the anterior speed of the tractor because of the expansion of the gliding of posterior driving tires, which is the reason behind the increase in the required time for any agricultural process. Hence, the fuel consumed will increase (Van Loon and Flores Rojas, 2022). As for a study made for identifying the influence of power take-off (PTO) on the quality of fuel consumption, it has been concluded that the increasing load of power take-off (PTO) with 16.7% leads to the increase in fuel consumption with 10.7% (Dahab et al., 2021). Another study by Xirui et al. (2016) to identify the influence of using a subsoiler plough on fuel consumption has observed a 22% increase in fuel consumed in an unstable condition compared with that of a stable one. The factors significantly impacting fuel consumption in the subsoiler plough are the speed of the tractor used in tillage, the reaction of soil, the cross-sectional area of tillage pieces, soil moisture content, and the operating depth (Rao and Chaudhary, 2018).

Despite the importance of the vibrating subsoiler plough, to date, not much research and development has been conducted to improve the performance of these types of ploughs. In addition, Iraqi farmers have a mistaken belief that using a subsoiler plough consumes large amounts of power, which leads to a reluctance to use it despite its importance (Hilal et al., 2021). Given the importance of developing the subsoil plough with vibrating wings, the study aims to:

1. Manufacture and develop the vibrating wings for the subsoil plough.
2. Evaluate the performance of the locally manufactured wings and their impact on the stability of the driver's seat, noise, slipping, and fuel consumption.

Material and Methods

Conventional and locally manufactured wings

The subsoiler plough used in the study is manufactured by the UZEL Company of Turkish origin. The conventional subsoiler plough consists of a frame, a single leg (shank), and the rake angle of the leg is 85° with vibrating wings. The two vibrating wings fixed on the foot are fixed at the lower end of the leg, and a wide share with a sharp edge is used to penetrate and cut the soil. The traditional vibrating wing (TD35) width is 35 cm with the outside edges of the wings

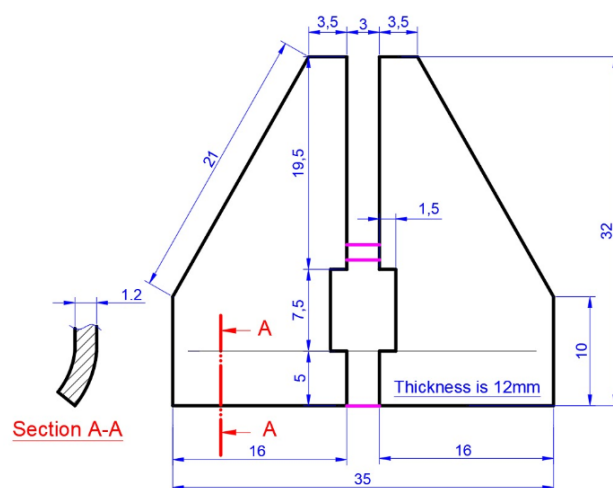


Fig. 1 Traditional vibrating wing

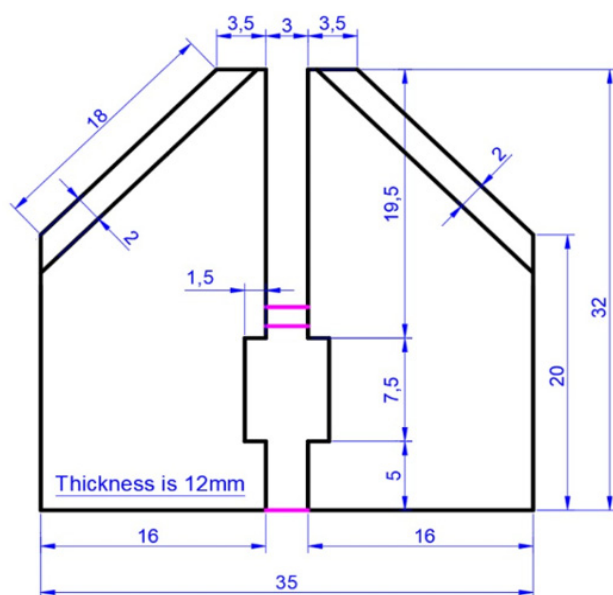


Fig. 2 Locally manufactured wings (ND35)

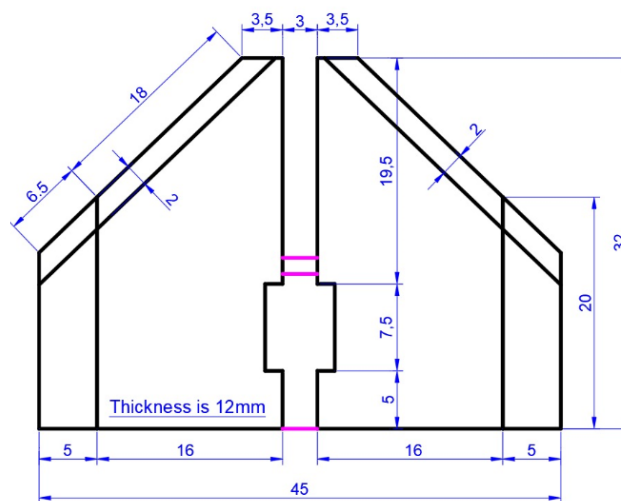


Fig. 3 Locally manufactured wings (ND45)

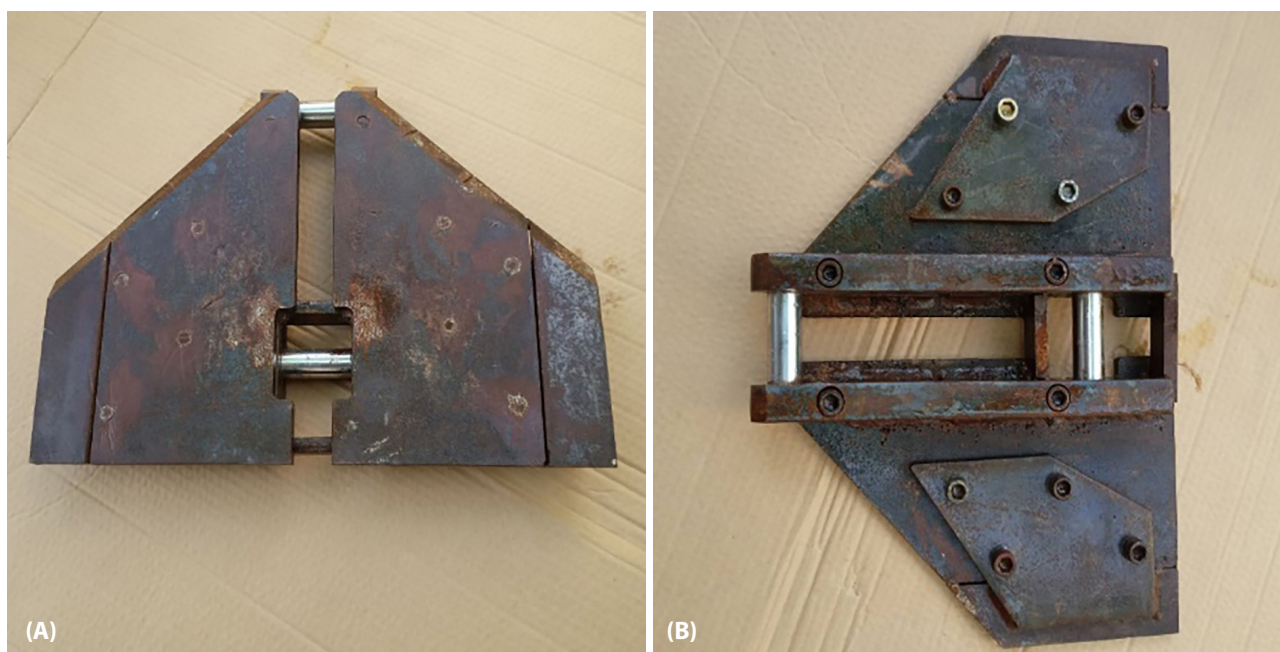


Fig. 4 Locally manufactured wings: (A) The view shows the top of the wings; (B) The view shows the bottom of the wings

sharp to cut off the sides, and the dimensions of the wings are shown in Fig. 1.

Two designs of locally manufactured wings (ND35 and ND45) with the widths of 35 cm and 45 cm were manufactured. The wings were made of steel with a 0.4% carbon content and a hardness of 70 HRB to withstand the stress imposed by the soil on the implement. The dimensions of the wings and the location of the subsoiler plough on the tractor are shown in Figs 2, 3, 4, and 5.



Fig. 5 Subsoiler plough with oscillating wings from the UZEL Company

Measuring soil properties

The method used to estimate the soil moisture content (MC) and soil bulk density is described by Black et al. (1965). The soil penetration index is evaluated according to Gill and Vandenberg (1968) at the depth levels of 0–10, 10–20, 20–30, 30–40, and 40–50 cm at many field parts, with three replicates for each treatment. The soil test results are shown in Table 1.

Table 1 Analysis of properties and soil texture at the site before the experiment

Soil depth (cm)	Bulk density ($\text{g}\cdot\text{cm}^{-3}$)	MC (%)	Soil penetration index ($\text{kN}\cdot\text{m}^{-2}$)
0–10	1.315	31.5	293.3
10–20	1.454	23.6	480.7
20–30	1.496	28.4	533.3
30–40	1.592	26.8	546.6
Soil texture	clay	silt	sand
Clay loam	34.45	45	20.55

Experiment parameters, statistical design, and indicators studied

The performance of the subsoiler plough was conducted on three factors: the types of vibrating wings (TD35, ND35, and ND45), and two angles of penetration 40° and 50° at a speed of wings vibration of 60 and $120 \text{ m}\cdot\text{s}^{-2}$. The experiment was analysed using a randomised complete block design with a split-plot design and Duncan's multiple range test at the 0.05% and 0.01% probability levels. The analysis of variance for the studied traits is presented in Table 2.

The indicators studied and the equations used to calculate them are:

1. The stability of the driver's seat was measured using a Uni-TUT315A device. The device above consists of a vibration sensor, which contains a magnet in front of it attached to the driver's seat to measure its vibration, as described by Hilal et al. (2021).
2. Noise was measured using an Extech 407750 device by means of the method described by Taha et al. (2022). The essential specifications of devices used for measured stability of the driver's seat and noise are presented in Table 3.

Table 2 Analysis of variance

Sources of difference	DF	Stability of driver's seat	Noise	Slipping	Fuel consumption
A: Types of vibrating wings	2	0.49694444 **	130.0308333**	43.25168939**	0.62602744NS
block	2	0.00194444 NS	0.2058333NS	2.58458779NS	0.05794011NS
a*block	4	0.00111111	4.9291667	2.12168043	0.11697969
B: Angle of penetration	1	0.00250000 NS	3.3002778NS	2.12673611NS	0.00087025NS
a*b	2	0.19750000 **	4.0502778*	34.67874939**	0.00430233NS
a*b*block	6	0.00416667	0.7552778	1.93108454	0.14004239
C: Speed of wings vibration	1	17.78027778**	548.3402778**	16.66462899**	60.88941003**
a*c	2	0.01194444 NS	1.1352778NS	34.89641255**	0.02063078NS
b*c	1	0.23361111 **	0.0025000NS	6.30461881*	0.61491736**
a*b*c	2	0.01694444NS	5.2225000*	8.62696515**	0.00366478NS
a*b*c*block	12	0.00944444	1.3205556	0.96160007	0.03793500

Table 3 Essential specifications of Uni-TUT315A and Extech 407750 devices

Term	Specifications
Model	Uni-TUT315A
Country of origin	China
Screen	LCD
Acceleration measurement range (m·s⁻²)	0.1–199.9
Velocity measurement range (cm·sec)	0.01–19.99
Error rate measurement	+5%
Acceleration measurement frequency range (Hz)	10–10000
Velocity measurement frequency range (Hz)	10–10000
Weight (g)	350
Device dimensions (mm)	166 × 80 × 30
Company link	https://emin.vn/en_US/uni-tut315a-uni-t-ut315a-vibration-tester-0-199-9m-s2-68298/pr.html
Model	Extech 407750
Country of origin	USA
Screen	LCD
Response rate (sec)	0.5
Audio captures (cm)	0.5
Measured frequency range (Hz)	31.5–8000
Accuracy (dB)	0.5 ± 1.5
Weight (g)	240
Device dimensions (mm)	256 × 80 × 38
Company link	https://www.extech.com/products/resources/407750_UM-en.pdf

3. The *slippage* of the tractor was calculated by Eq. 1:

$$\text{slippage (\%)} = \frac{\text{travel speed with zero drawbar pull} - \text{travel speed with generating a drawbar pull}}{\text{travel speed with zero drawbar pull}} \quad (1)$$

4. The fuel consumption of the tractor was calculated as described by Awwad et al. (2023) and presented by Eq. 2:

$$\text{fuel consumption (l}\cdot\text{h}^{-1}\text{)} = \frac{\text{amount of fuel consumed (ml)}}{\text{actual time to complete the transaction (sec)}} \cdot 3.6 \quad (2)$$

Result and Discussion

The effect of the types of vibrating wings and angle of penetration on the characteristics studied

Table 4 shows statistical analysis data on the stability of the driver's seat, noise, slipping, and fuel consumption for each type of vibrating wing according to the angle of penetration. Overall, there was a statistically significant higher stability of the driver's seat, noise, and slipping, except for fuel consumption. No significant difference was observed in TD35 compared to ND35 and ND45 for both angles of penetration. In particular, the stability of the driver's seat and noise in TD35 was found to be higher than that in both new designs, with higher values of approximately $2.450 \text{ m}\cdot\text{s}^{-2}$ and 86.4 dB . Vibration and noise values are considered higher than the values specified by international organisations specialised in the field of

protecting farmers in agricultural work (European Parliament Directive 2003/10/EC). The slipping and fuel consumption results showed a convergence in results between TD35 and ND45. The lowest results were recorded in ND35, estimated at 7.948% and $4.563 \text{ L}\cdot\text{hr}^{-1}$ at the penetration angles of 50° and 40° , respectively.

Table 4 shows the effect of penetration angles on the characteristics studied. In the penetration angles of 40° , the stability of the driver's seat was approximately $1.934\text{--}2.40 \text{ m}\cdot\text{s}^{-2}$, with a maximum variability of 24% . Noise was in the range of approximately $79.266\text{--}86.400 \text{ dB}$ and showed fluctuations of up to 9% . Slipping showed a change of up to 31% in the range of approximately $11.619\text{--}15.222\%$. Moreover, fuel consumption was in the range of $4.563\text{--}5.032 \text{ L}\cdot\text{hr}^{-1}$. In the penetration angles of 50° , the stability of the driver's seat and noise were $1.983\text{--}2.450 \text{ m}\cdot\text{s}^{-2}$ and $79.916\text{--}85.050 \text{ dB}$, respectively. Slipping and fuel consumption were $7.948\text{--}13.317\%$ and $4.606\text{--}5.050 \text{ L}\cdot\text{hr}^{-1}$, respectively. As shown in Table 4, the overlap between ND35 and 40° recorded the lowest values for the stability of the driver's seat, noise, and fuel consumption. Still, on the other hand, the overlap between ND35 and 50° recorded the lowest values for slipping (7.948%).

The effect of the types of vibrating wings and speed of wing vibration on the characteristics studied

Table 5 shows the statistical analysis data on the stability of the driver's seat, noise, slipping, and fuel consumption for each type and speed of vibrating wing. Overall, there was no significant difference in the stability of the driver's seat, noise, and fuel consumption, except for slipping, with an important difference observed in TD35 compared to ND35 and ND45 for the wing speeds of 60 and $120 \text{ m}\cdot\text{s}^{-2}$.

Table 4 The relationship between the types of vibrating wings with the angle of penetration and its effect on the characteristics studied

Types of vibrating wings	Angle of penetration ($^\circ$)	Stability of driver's seat ($\text{m}\cdot\text{s}^{-2}$)	Noise (dB)	Slipping (%)	Fuel consumption ($\text{l}\cdot\text{h}^{-1}$)
TD35	40	2.400 A	86.400 A	14.020 A	5.032
	50	2.450 A	85.050 B	13.138 AB	5.050
ND35	40	1.934 D	79.266 D	11.619 BC	4.563
	50	2.134 C	80.000 CD	7.948 D	4.606
ND45	40	2.283 B	81.116 C	15.222 C	4.814
	50	1.983 D	79.916 CD	13.317 AB	4.783

Table 5 The relationship between the types of vibrating wings and the speed of wings vibration and the effect on the characteristics studied

Types of vibrating wings	Speed of wings vibration ($\text{m}\cdot\text{s}^{-2}$)	Stability of driver's seat ($\text{m}\cdot\text{s}^{-2}$)	Noise (dB)	Slipping (%)	Fuel consumption ($\text{l}\cdot\text{h}^{-1}$)
TD35	60	1.700	82.166	12.304 B	3.781
	120	3.150	89.283	14.854 A	6.301
ND35	60	1.316	75.634	11.242 B	3.241
	120	2.750	83.643	8.325 D	5.928
ND45	60	1.467	76.366	13.627 A	3.500
	120	2.800	84.666	9.912 C	6.096

Table 6 The relationship between penetration angle with the speed of wing vibration and the effect on the characteristics studied

Angle of penetration (°)	Speed of wings vibration ($\text{m}\cdot\text{s}^{-2}$)	Stability of driver's seat ($\text{m}\cdot\text{s}^{-2}$)	Noise (dB)	Slipping (%)	Fuel consumption ($\text{l}\cdot\text{h}^{-1}$)
40	60	1.423 D	78.366	13.053 A	3.633 C
	120	2.989 A	86.155	10.855 B	5.973 B
50	60	1.567 C	77.745	11.730 B	3.381 D
	120	2.812 B	85.566	11.206 B	6.245 A

In particular, the stability of the driver's seat, noise, slipping, and fuel consumption in TD35 was higher than that in ND35 and ND45 for both wing speeds (the highest values were $3.150 \text{ m}\cdot\text{s}^{-2}$, 86.4 dB, 14.854%, and $6.301 \text{ l}\cdot\text{h}^{-1}$); except at an overlap between ND45 and $60 \text{ m}\cdot\text{s}^{-2}$. The stability of the driver's seat and noise values are higher than the values of natural limits according to the European Parliament Directive 2003/10/EC which addresses the minimum health and safety requirements related to workers' exposure to physical agents, specifically noise. The directive establishes an average upper limit of 85 dB for noise exposure during an eight-hour shift, aiming to prevent hearing impairments among workers. This standard aligns with the guidelines of the International Labour Organisation (ILO), as indicated in its code of practice (Vallone et al., 2016).

Table 5 shows the effect of the speed of wing vibration on the characteristics studied. In the wings vibration of $60 \text{ m}\cdot\text{s}^{-2}$, the stability of the driver's seat was approximately $1.316\text{--}1.700 \text{ m}\cdot\text{s}^{-2}$, with a maximum variability of 29%. Noise was approximately 75.634–82.166 dB and showed up to 8.6% fluctuations. Slipping showed a change of up to 21% in the range of approximately 11.242–13.627%. Moreover, fuel consumption was in the range of 3.241–3.781 $\text{l}\cdot\text{h}^{-1}$. In the wings vibration of $120 \text{ m}\cdot\text{s}^{-2}$, the stability of the driver's seat and noise were $2.750\text{--}3.150 \text{ m}\cdot\text{s}^{-2}$ and 83.643–89.283 dB, respectively. Slipping and fuel consumption were 8.325–14.854% and $5.928\text{--}6.301 \text{ l}\cdot\text{h}^{-1}$, respectively. As shown in Table 5, the overlap between ND35 and $60 \text{ m}\cdot\text{s}^{-2}$ recorded the lowest values for the stability of the driver's seat, noise, and fuel consumption, which were $1.316 \text{ m}\cdot\text{s}^{-2}$, 75.634 dB, and 3.241 $\text{l}\cdot\text{h}^{-1}$, respectively. In contrast, the overlap

between ND35 and $120 \text{ m}\cdot\text{s}^{-2}$ recorded the lowest values for slipping 8.325%.

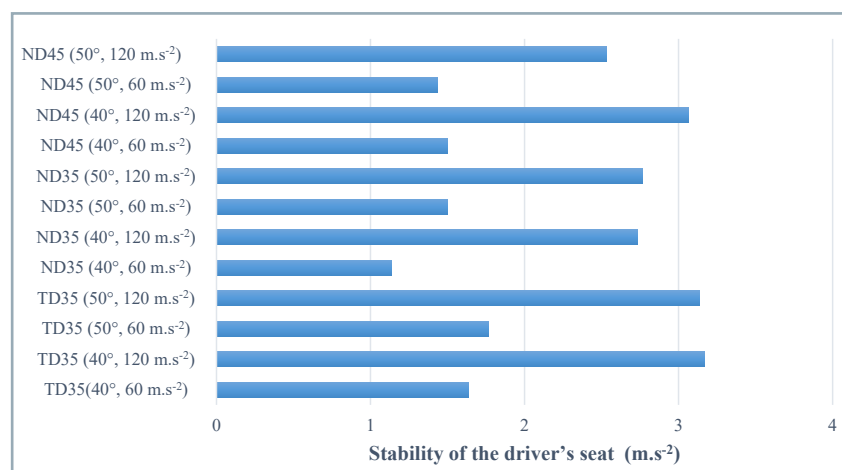
The effect of penetration angle and the speed of wing's vibration on the characteristics studied

Table 6 shows the statistical analysis results of the study characteristics data for each angle of penetration according to the speed of wings vibration. There was a significant difference in the stability of the driver's seat, slipping, and fuel consumption, except for noise. According to the results, the stability of the driver's seat and noise for the interaction between the 40° penetration angle and $120 \text{ m}\cdot\text{s}^{-2}$ wing vibration is higher than all the other interactions; however, the results roughly converged with the measurement guidelines previously approved by ISO 2631-5 (2004) and European Parliament and Council Directive 2002/44/EC. In particular, the higher value of slipping was 13.053% in the overlap between 40° penetration angles and $60 \text{ m}\cdot\text{s}^{-2}$ wing vibration compared to all overlaps. The overlap between the 50° penetration angle and $120 \text{ m}\cdot\text{s}^{-2}$ wing vibration was recorded as a higher value

of fuel consumption of approximately $6.245 \text{ l}\cdot\text{h}^{-1}$. Some results agree with Hilal et al. (2021), who concluded that increasing the penetration angles leads to decreased vibration on the tractor driver's seat.

The effect of the triple interaction of factors on the stability of driver's seat

Figure 6 shows the influence of the type of vibrating wing according to the angle of penetration and speed of the vibrating wing on the stability of the driver's seat. The results indicated that values were influenced positively by ND35 and ND45 and the penetration angles at both speeds of the vibrating wing. The stability of the driver's seat at ND35 and ND45 and the penetration angles in both speeds of the vibrating wing were considerably lower than those of TD35 with all treatments. At the same time, the overlap between ND35, 40° penetration angles, and $60 \text{ m}\cdot\text{s}^{-2}$ wing vibration recorded the lowest stability of the driver's seat, which was $1.134 \text{ m}\cdot\text{s}^{-2}$. The reason may be that the cutting process was improved using the new design, which reduced the reaction of the soil

**Fig. 6** The relationship between the triple interaction of factors on driver's seat

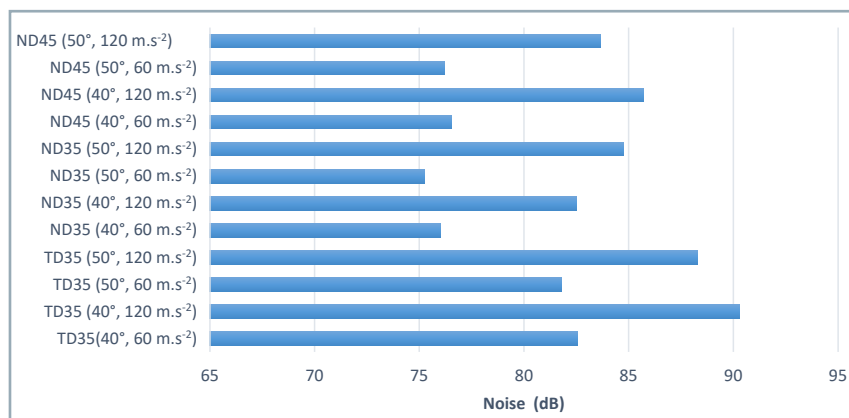


Fig. 7 The relationship between the triple interaction of factors and noise

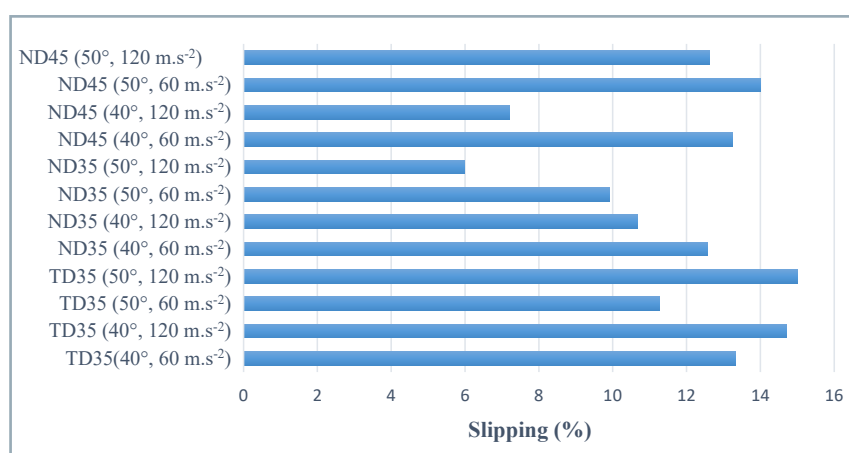


Fig. 8 The relationship between the triple interaction of factors and slipping

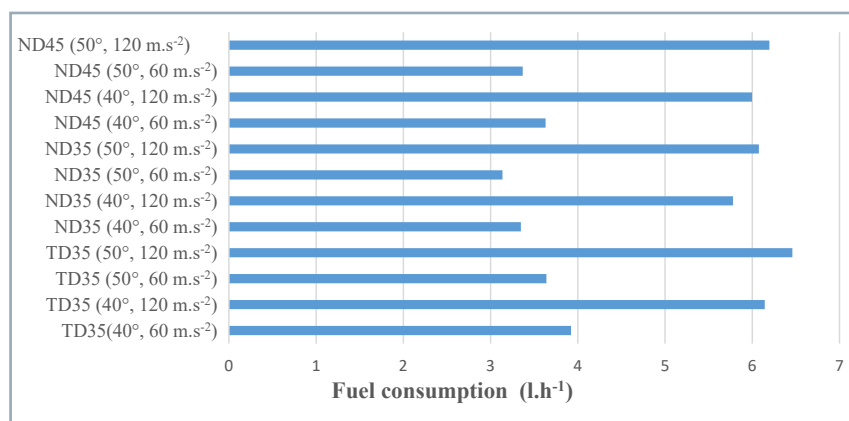


Fig. 9 The relationship between the triple interaction of factors and fuel consumption

on the wings, reflected in reduced vibration. Otherwise, the results showed that the stability of the driver's seat was higher at TD35 in the 40° and 50° penetration angles with 120 m.s⁻² wing vibration, with the values being 3.167 and 3.134 m.s⁻².

The effect of the triple interaction of factors on noise

Figure 7 shows the effect of the type of vibrating wing according to the angle of penetration and speed of the vibrating wing on noise. The results indicated that noise values were influenced positively by ND35 and ND45 and the penetration angles at both speeds of the vibrating wing. The noise at ND35 and ND45 and the penetration angles at both speeds of the vibrating wing were considerably lower than those of TD35 with all treatments. At the same time, the overlap between ND35 in the 40° and 50° penetration angles and 60 m.s⁻² wing vibration recorded the lowest noise, which was 75.234 and 76.034 dB, respectively. The reason may be that the cutting process was improved using the new design, which reduced the load on the agricultural tractor engine, reflected in reduced noise. Furthermore, the results showed that noise was higher at TD35 in the 40° and 50° penetration angles with 120 m.s⁻² wing vibration, which was 90.26 and 88.3 dB. These results are higher than international recommendations stating that the noise level should not exceed 85 dB during eight working hours, which was approved by ISO 2631-5 (2004) and European Parliament and Council Directive 2002/44/EC.

The effect of the triple interaction of factors on slipping

Figure 8 shows the effect of the type of vibrating wing according to the angle of penetration and speed of the vibrating wing on slipping. The results indicated that slipping values were influenced positively by ND35 and ND45 and the penetration angles at both speeds of the vibrating wing. The slipping at ND35 and ND45 and the penetration angles at both speeds of the vibrating wing were considerably lower than those of TD35 with all treatments, except for the overlap between ND45 in the 50° penetration angle and 60 m.s⁻² wing vibration. At the same time,

the overlap between ND35 in the 50° penetration angle and 120 m·s⁻² wing vibration recorded the lowest slipping, which was 5.98%. The results showed the second least slipping reading at the overlap between ND45 in the 40° penetration angle and 120 m·s⁻² wing vibration. Furthermore, the results showed that slipping was higher at TD35 in the 40° and 50° penetration angles with 120 m·s⁻² wing vibration, but slipping remains within the acceptable limits. Some results agree with Abdullah and Hilal (2017) and Hilal et al. (2021), who concluded that increasing the penetration angles leads to increased slipping.

The effect of the triple interaction of factors on fuel consumption

Figure 9 shows fuel consumption variations depending on the type of vibrating wing according to the angle of penetration and speed of the vibrating wing. Using the new designs ND35 and ND45 with the penetration angles at both speeds of the vibrating wing causes a decrease in fuel consumption. All factors facilitating and accelerating the reaction between factors affect fuel consumption. The fuel consumption at ND35 and ND45 and the penetration angles at both speeds of the vibrating wing were considerably lower than those of TD35 with all treatments, except for the overlap between ND45 in the 50° penetration angle and 120 m·s⁻² wing vibration. At the same time, the overlap between ND35 in the 50° penetration angle and 60 m·s⁻² wing vibration recorded the lowest fuel consumption, which was 3.136 l·h⁻¹. The results showed the second least fuel consumption reading at the overlap between ND35 in the 40° penetration angle and 60 m·s⁻² wing vibration. Furthermore, the results showed that fuel consumption was higher at TD35 in the 40° and 50° penetration angles with 120 m·s⁻² wing vibration. In addition, the results showed that increasing the speed of wing vibration leads to increased fuel consumption. These results agree with Taha et al. (2022), who concluded that fuel consumption rises due to increased engine load.

Conclusion

The following conclusions can be drawn from the results: ND35 achieved the best results for the stability of the driver's seat and noise, with results close to the recommendations proposed by European Parliament Directive 2003/10/EC. Moreover, slipping and fuel consumption for ND35 were reduced, with the estimated values of 7.948% and 4.563 l·h⁻¹ at the penetration angles of 50° and 40°, respectively. The wing vibration of 60 m·s⁻² recorded the best results for all the characteristics studied. In addition, the 40° penetration angle achieved better results when interacting with the new designs and wing vibration of 60 m·s⁻². Otherwise, the TD35 record had a negative impact on the stability of the driver's seat, noise, slipping, and fuel consumption at both penetration angles and wing vibration. Finally, the researchers suggest studying the power spent during the operation of new designs for future work.

Acknowledgment

The authors would like to thank Mosul University and Wageningen University & Research for their support during the study.

References

- ABDULLAH, A. A. – HILAL, Y. Y. 2017. Effect of the distances between subsoiler plow tines bilateral and penetration angles on some performance indicators field. In *Mesopotamia Journal of Agriculture*, vol. 45, no. 1, pp. 273–286.
- ABOUEL-SEOUD, S. A. H. 2019. Control of driver whole-body vibration ride comfort in agricultural tractor. In *Agricultural Engineering International: CIGR Journal*, vol. 21, no. 2, pp. 40–51. <https://cigrjournal.org/index.php/Ejournal/article/view/5072>
- ASKARI, M. – SHAHGHOLOI, G. – ABBASPOUR-GILANDEH, Y. 2019. New wings on the interaction between conventional subsoiler and paraplow tines with the soil: effects on the draft and the properties of soil. In *Archives of Agronomy and Soil Science*, vol. 65, no. 1, pp. 88–100. DOI: <https://doi.org/10.1080/03650340.2018.1486030>
- AWWAD, A. A. – HILAL, Y. Y. – RAJAB, R. H. 2023. The effect of diesel fuel improvers on the vibrations, noise and fuel consumption of the agricultural tractor engine during the tillage process. In *IOP Conference Series: Earth and Environmental Science*, vol. 1213, article no. 012098. DOI: <https://doi.org/10.1088/1755-1315/1213/1/012098>
- BLACK, C. A. – EVANS, D. D. – WHITE, J. L. – ENSMINGER, L. E. – CLARK, F. E. 1965. *Methods of Soil Analysis. Part 1. Physical and Mineralogical Properties, Including Statistics and Sampling*. Agronomy Monograph No. 9. Madison, Wiscon, USA : American Society of Agronomy, Inc., 836 pp. DOI: <https://doi.org/10.2134/agronmonogr9.1>
- CUTINI, M. – BRAMBILLA, M. – BISAGLIA, C. 2017. Whole-body vibration in farming: Background document for creating a simplified procedure to determine agricultural tractor vibration comfort. In *Agriculture*, vol. 7, no. 10, article no. 84. DOI: <https://doi.org/10.3390/agriculture7100084>
- DAHAB, M. H. – KHEIRY, A. N. O. – TALHA, T. H. A. 2021. A computer model of fuel consumption estimation for different agricultural farm operations. In *International Journal of Advanced Technology & Science Research*, vol. 2, no. 2, pp. 72–85. Available at: https://ijatsr.org/assets/papers/2021/feb/ijatsr_02_07.pdf
- DIRECTIVE 2002/44/EC of the European Parliament and of the Council of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (sixteenth individual directive within the meaning of Article 16(1) of Directive 89/391/EEC).
- DIRECTIVE 2003/10/EC of the European Parliament and of the Council of 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise) (seventeenth individual directive within the meaning of Article 16(1) of Directive 89/391/EEC).
- FRANCAVIGLIA, R. – ALMAGRO, M. – VICENTE-VICENTE, J. L. 2023. Conservation agriculture and soil organic carbon: Principles, processes, practices and policy options. In *Soil Systems*, vol. 7, no. 1, article no. 17. DOI: <https://doi.org/10.3390/soilsystems7010017>
- GILL, W. R. – VANDENBERG, G. E. 1968. *Soil Dynamics in Tillage and Traction*. Agriculture Handbook no. 316. USDA Agricultural Research Service. Washington, D.C. : US Government Printing Office, 511 pp. Available at: <https://books.google.iq/books?id=ynowAAAAYAAJ&hl=ar&pg=PP1#v=onepage&q&f=true>
- HILAL, Y. Y. – AL-RAJABO, S. A. J. – DAHHAM, G. A. 2021. The effects of vibrating wings subsoiler plow on driver's seat of agricultural tractors and mechanization performance. In *Soil and Tillage Research*, vol. 205, article no. 104806. DOI: <https://doi.org/10.1016/j.still.2020.104806>
- ISO 2631-5:2004. Mechanical vibration and shock – evaluation of human exposure to whole-body vibration – Part 5: Method for evaluation of vibration containing multiple shocks.

- JEBUR, H. A. 2023. A review: Machine relationship with the tractor and its effect on the productivity and compaction of agricultural soil. In *University of Thi-Qar Journal of Agricultural Research*, vol. 12, no. 1, pp. 22–43. DOI: <https://doi.org/10.54174/utjagr.v12i1.237>
- KALFAS, D. – KALOGIANNIDIS, S. – PAPADEVANGELOU, O. – MELFOU, K. – CHATZITHEODORIDIS, F. 2024. Integration of technology in agricultural practices towards agricultural sustainability: A case study of Greece. In *Sustainability*, vol. 16, no. 7, article no. 2664. DOI: <https://doi.org/10.3390/su16072664>
- LI, X. – WANG, S. – MENG, H. – QU, Q. – JIA, Y. 2022. Research on drag reduction mechanism of pneumatic subsoiler and establishment of resistance mathematical model. In *Canadian Journal of Soil Science*, vol. 102, no. 2, pp. 531–548. DOI: <https://doi.org/10.1139/cjss-2021-0101>
- MOJŽIŠ, M. – JOBBÁGY, J. – RATAJ, V. – ZSEMBELI, J. 2024. Impact of machinery passages on soil compaction in field conditions. In *Acta Technologica Agriculturae*, vol. 27, no. 2, pp. 116–124. DOI: <https://doi.org/10.2478/ata-2024-0016>
- PORTO ALE, L. – SOARES ARCOVERDE, S. N. – ALVES DE SOUZA, C. M. – FERREIRA CRESTANI, A. – LEYVA RAFULL, L. Z. 2023. Evaluation of tractor traffic on soil physical properties and their relationship with white oat yield in no-tillage. In *Revista de Ciencias Agroveterinarias*, vol. 22, no. 4, 674–684. DOI: <https://doi.org/10.5965/223811712242023674>
- RAO, G. – CHAUDHARY, H. 2018. A review on effect of vibration in tillage application. In *IOP Conference Series: Materials Science and Engineering*, vol. 377, article no. 012030. IOP Publishing. DOI: <http://dx.doi.org/10.1088/1757-899X/377/1/012030>
- SHAHGHOLI, G. – FAZELI, S. – MOUSAVI, S. H. 2019. Vibration evaluation of the driver's seat of MF 285 tractor in conducting the tillage operations. In *Emirates Journal for Engineering Research*, vol. 25, no. 1, pp. 1–11. Available at: <https://scholarworks.uaeu.ac.ae/ejer/vol25/iss1/2/>
- SHAHGHOLI, G. – MOINFAR, A. – KHORAMIFAR, A. – MACIEJ, S. – SZYMANEK, M. 2023. Investigating the effect of tractor's tire parameters on soil compaction using statistical and adaptive neuro-fuzzy inference system (ANFIS) methods. In *Agriculture*, vol. 13, no. 2, article no. 259. DOI: <https://doi.org/10.3390/agriculture13020259>
- SHARMA, P. K. – KUMAR, S. 2023. Soil Strength and Plant Growth. In *Soil Physical Environment and Plant Growth: Evaluation and Management*. Cham : Springer International Publishing, pp. 205–229. DOI: http://dx.doi.org/10.1007/978-3-031-28057-3_9
- SINGH, A. – SAMUEL, S. – DHABI, Y. K. – SINGH, H. 2023. Whole-body vibration: Characterization of seat-to-head transmissibility for agricultural tractor drivers during loader operation. In *Smart Agricultural Technology*, vol. 4, article no. 100164. DOI: <https://doi.org/10.1016/j.atech.2022.100164>
- SYROMYATNIKOV, Y. – VOINASH, S. – TROYANOVSKAYA, I. – ZAGIDULLIN, R. – TIKHONOV, E. – OREKHOVSKAYA, A. 2024. Chisel tillage under spring barley in the forest-steppe. In *Acta Technologica Agriculturae*, vol. 27, no. 1, pp. 30–34. DOI: <https://doi.org/10.2478/ata-2024-0005>
- TAHA, H. T. – HILAL, Y. Y. – RAJAB, R. H. 2022. Effects of enhancer diesel fuel and vibrating wings subsoiler plow on the performance of an agricultural tractor. In *International Journal of Applied Sciences and Technology*, vol. 4, no. 3, pp. 71–80. DOI: <http://dx.doi.org/10.47832/2717-8234.12.7>
- VALLONE, M. – BONO, F. – QUENDLER, E. – FEBO, P. – CATANIA, P. 2016. Risk exposure to vibration and noise in the use of agricultural track-laying tractors. In *Annals of Agricultural and Environmental Medicine*, vol. 23, no. 4, pp. 591–597. DOI: <https://doi.org/10.5604/12321966.1226852>
- VAN LOON, J. – FLORES ROJAS, M. 2022. Training of Trainers Manual on the Operation, Maintenance and Repair of Farm Machinery. Rome : FAO, 100 pp. ISBN 978-92-5-136071-2. DOI: <https://dx.doi.org/10.4060/cb9549en>
- VANDERHASSELT, A. – COOL, S. – D'HOSE, T. – CORNELIS, W. 2023. How tine characteristics of subsoilers affect fuel consumption, penetration resistance and potato yield of a sandy loam soil. In *Soil and Tillage Research*, vol. 228, article no. 105631. DOI: <https://doi.org/10.1016/j.still.2022.105631>
- XIRUI, Z. – CHAO, W. – ZHISHUI, C. – ZHIWEI, Z. 2016. Design and experiment of a bionic vibratory subsoiler for banana fields in southern China. In *International Journal of Agricultural and Biological Engineering*, vol. 9, no. 6, pp. 75–83. DOI: <http://dx.doi.org/10.3965/j.ijabe.20160906.1923>
- ZENG, X. 2016. Modeling predictors of whole body vibration exposure among Saskatchewan farmers: A key step in low back disorder prevention. Doctoral dissertation. Saskatoon, Canada : University of Saskatchewan, 121 pp. Available at: <https://harvest.usask.ca/server/api/core/bitstreams/dd747f7f-d73b-459a-b127-4ac3e5a2f363/content>

