

THE EFFECT OF PLOUGH MODERNIZATION ON FUEL CONSUMPTION DURING PLOUGHING AND SUBSOIL BULK DENSITY

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ARTICLE INFO	ABSTRACT
<i>Article history:</i> Received: September 2025 Received in the revised form: February 2026 Accepted: May 2026	This study attempts to address the problem of excessive soil compaction in the subsoil layer caused by the movement and operation of agricultural machinery by modernizing the plough design to combine two operations with high energy requirements, ploughing and subsoiling. The aim of this study was to modernize and develop the design of the share plough by adding an additional frame (heavy-duty tines) on which the mounted working elements (straight type chisel spike, two-heart type chisel spike, duck foot type chisel spike). The effect of the plough modernization was to destroy the plough pan, leading to a decrease in the bulk density of the soil in the subsoil layer. However, when tines with a duck foot (sweep) type chisel spike were used, an increase in soil bulk density was observed in the layer below the working depth of the tool. The modernization of the plough resulted in the increase in fuel consumption per units' area during ploughing related to the area cultivated. Using a modernized plough allows two energy-intensive operations – ploughing and subsoiling – to be combined in a single pass.
<i>Keywords:</i> plough pan, bulk density, fuel consumption	

Introduction

The compaction of the soil caused by machinery traffic in agriculture is a big problem across wide areas of the world and is one of the most important factors causing the physical degradation of the soil and it has considerable consequences for crop production and the environment (Keller and Arvidsson, 2004; Filipović, 2011). The scale of this problem can be demonstrated by the fact that, according to Domżał and Hodara (1990), during the growing season the soil in the surface layer is subjected to compaction on average 2.5 to 5 times, and

in some cases even 8 times. They also claim that at the same time, the uncompacted soil surface may occupy only 10% of the total field area. Plough pan is a compacted layer of soil that is difficult for roots or water to penetrate (Gliński et al., 2011). It often forms just below the depth of ploughing, when, over the years, repeated ploughing orients all the soil particles in the same direction and depth, causing a compacted layer of soil (Hossne et al., 2015). Anusontpornperm et al., (2014) mentioned that this layer has a bulk density value higher than $1.65 \text{ g} \cdot \text{cm}^{-3}$, which is considered to be the critical value for root penetration deep into the soil. It has a low permeability and infiltration rate which increases the potential for runoff and erosion, limited productivity, the accumulation of lower amounts of water and makes plant susceptible to temporal drought stress (Manor and Clark, 2001; Raza et al., 2005; Esser, 2016). A plough pan is mainly formed when ploughing is carried out, when the tractor wheels move along the bottom of the furrow (Vistro et al., 2022). The compaction then consists of tractor wheel pressure, blade pressure and plough shoe pressure. Excessive compaction of the subsoil also occurs with agricultural machinery and implements other than the plough, e.g. in ploughless technologies (Pisker 2006). This occurs when basic cultivation is carried out with heavy tines fitted with duck foot type chisel spikes, the total working width of which is the working width of the implement (as in the case of ploughing). Such tines work well for stubble cultivation but can lead to excessive compaction below the cultivation layer during primary tillage (Tenu et al., 2018; Mileusnic et al., 2022).

The aim of this study is to modernize and develop the moldboard plough design by adding an extra frame with chisel tines, that works below the ploughing layer immediately after wheel pass on the bottom of the furrow, which has been previously opened in the last run of the ploughing operation and after first and second plough bodies (Figure 1). This modernization makes it possible to combine the two energy-intensive operations of ploughing and subsoiling. The working elements of the additional frame working only at a depth of 0.1-0.15 m, on soil uncovered by the plough bodies during ploughing. This leads to soil loosening, therefore reduced subsoil bulk density.

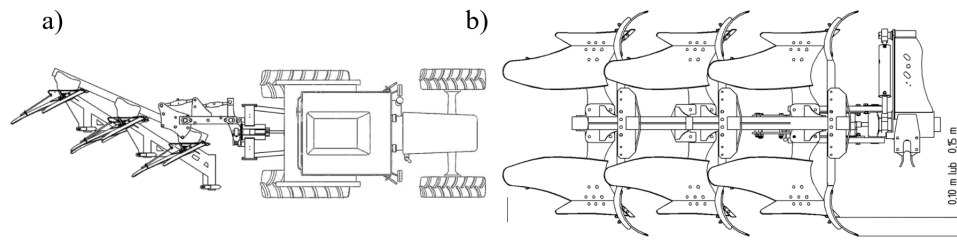


Figure 1. Schematic drawing of the modernized plough: a) – top view of modernized plough, b) – side view of modernized plough.

Materials and Methods

A mounted type of reversible moldboard plough (Unia Ibis M 3+1), in-furrow ploughing system was used. The plough was modernized by adding an extra component (frame with chisel tines) which was combined to the frame of the plough by Henryk Batyra Company in Lublin, Poland. In the field tests New Holland TD5030 tractor was used (Fig. 2).



Figure 2. View of agricultural tractor with modernized plough during field test

The arrangement of the chisel tines has been designed so that their operation and the chisel spikes mounted on them minimize the negative impact of the machine on the subsoil. The first of these is located directly behind the rear wheel of the tractor moving in the furrow created during the previous pass. Ploughing with the wheels in the furrow causes the tractor to tilt, resulting in greater pressure on the soil than the pressure exerted by wheels moving on-land. The second and third chisel tines are located behind the first and second plough bottoms, respectively, in the middle of the ploughshare width (Sprawka, 2022).

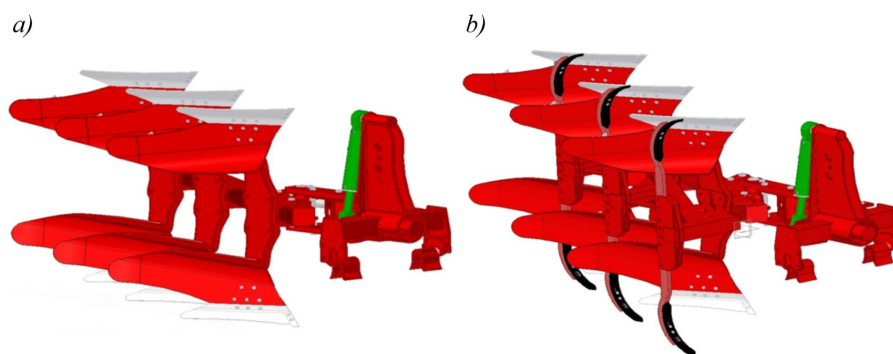


Figure 3. Modernization of the Unia Ibis M 2+1 plough; a) reversible 3 bottom moldboard plow, b) modernized reversible 3 bottom moldboard plow

Three sets of standard chisel spikes were used as working elements of the chisel tines: twisted heart type chisel spikes, twisted straight type chisel spikes and duck foot or sweep type chisel spikes. Their basic dimensions are shown in figure 4.

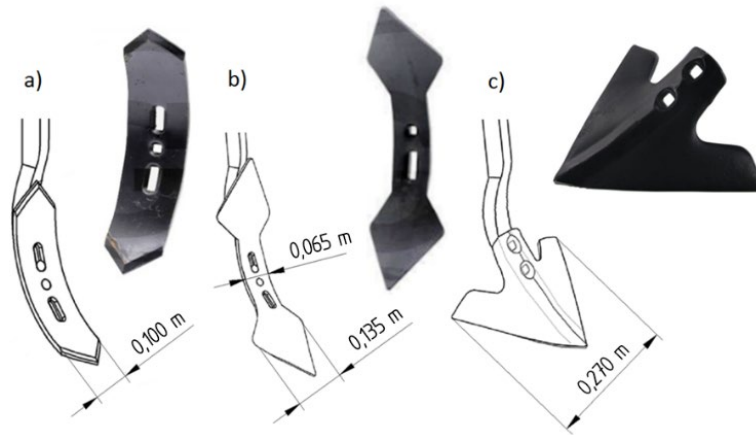


Figure 4. Used working elements: a) straight type chisel spike, b) two-heart type chisel spike, c) duck foot type chisel spike

A SRTIME flow meter was used to measure fuel consumption (company SRTIME GP Pawłowski & Jelonek, manufactured in Poland). It records the instantaneous fuel consumption of the tractor engine ($L \cdot h^{-1}$). It was connected to the tractor's fuel system between the fuel tank and the fuel pump (Fig. 5).



Figure 5. the fuel flow meter mounted on the tractor.

In addition, it also measures the amount of excess fuel that returns to the tank. This allows the actual fuel consumption of the tractor engine to be determined.

Ploughing was performed at three different working speeds (The three elected speeds should be mentioned in two brackets). Three theoretical speeds of plowing were chosen and determined by the tractor's transmission ratios and a constant engine speed while the plow bottoms' share almost touching the soil surface. These speeds do not consider the slip of the drive wheels during operation. Then, the actual working speed was determined via a GPS receiver, model BU-353-S4 (Fig. 6).



Figure 6. the GPS receiver used, model BU-353-S4 (own work)

Using ploughing efficiency (expressed as actual forward speed and total working width) and hourly fuel consumption, fuel consumption per unit area was calculated using the following formula:

$$Q_f = Q_i \cdot (0.36 \cdot W \cdot vV_a)^{-1} \quad (1)$$

where:

- Q_f – Fuel consumption per unit area, ($L \cdot ha^{-1}$)
- Q_i – Hourly fuel consumption, ($L \cdot h^{-1}$)
- W – Total working width, (m)
- V_a – Actual forward speed, ($m \cdot s^{-1}$)

Using a coping adjustment, a constant ploughing depth of 0.20 m for the primary tillage by the moldboard plough was assumed. Total working width was 1.14 m (PN-90/R-55021). Before ploughing, the initial physical properties of the soil were determined (Table1).

Table 1.
Some initial soil properties.

Location	Soil depth (m)	C Content	Organic maters	Soil particles (%)			Initial Soil physical properties		
				Sand	Silt	Clay	Bulk density ($\text{g}\cdot\text{cm}^{-3}$)	Porosity (%)	Cone index (MPa)
Fellin	0-0.20	0.97	2.48	35.18	59.84	4.98	1.46	44.91	1.64
	0.20-0.25	0.67	2.04	35.12	59.65	5.23	1.70	35.85	2.92
	0.25-0.30	0.35	1.63	32.82	61.61	5.57	1.75	33.96	3.52
	0.30-0.35	0.25	1.68	35.78	58.97	5.25	1.68	36.6	2.52

Among other things, this allowed the average moisture content of the soil to be calculated, which was around 20%. The experiment was conducted using the complete randomized block design with three replications. The first treatment was the tines setting (depth and working width below the moldboard plough depth level) with seven levels: first level was the NO TINE which represented the normal plough without an extra component (control), the second and third level were the TINE1D10 and TINE1D15 which represented a 0.135 m width two-heart types chisel spikes which worked below the ploughing layer at the depth of 0.10 and 0.15 m respectively, TINE2D10 and TINE2D15 were the fourth and fifth levels which represented a 0.10 m width straight type chisel spikes which worked below the ploughing layer at the depth of 0.10 and 0.15 m respectively, the last two levels were the TINE3D10 and TINE3D15 which represented 0.27 m width duck foot type chisel spikes that worked below the ploughing layer at the depth of 0.10 and 0.15 m respectively (Figure 1.). The second treatment was three forward speeds $V_1 = 1.94$, $V_2 = 3.9$ and $V_3 = 6.3 \text{ km}\cdot\text{h}^{-1}$.



Figure 7. the soil outcrop and device for collecting rectangular soil samples

To determine the soil bulk density, one month after the field work has been conducted, a device for collecting rectangular soil samples (dimension: 0.2x0.05, 0.05 m) was used after wheel pass on the furrow (with and without tines action), at three levels of the soil depth below the ploughing layer (20 cm) which were 0–5, 5–10 and 10–15 cm, that corresponded to the soil depth of 20–25, 25–30, 30–35 cm from the soil surface (Fig. 7).

This rectangular soil samples device is covered by the protection right number 74035 for the utility model granted by the Patent Office of the Republic of Poland.

The collected soil samples were subjected to laboratory testing in accordance with PN-EN ISO 11272:2017-05, after determining the volume of a single working space of the device. The average bulk density of dry matter was determined for each soil level tested. Three repetitions were performed for each test variant.

Results and Discussion

The average fuel consumption per unit area ($L \cdot ha^{-1}$) measured for all tested variants, according to Tukey's multiple comparison test ($p \leq 0.05$), shows statistically significant differences in relation to the control measurement (NO TINE). For the tested forward speeds, the lowest values were obtained for variant NO TINE. They amounted to $38.24 L \cdot ha^{-1}$, $26.85 L \cdot ha^{-1}$ and $20.28 L \cdot ha^{-1}$, respectively (Fig. 8).

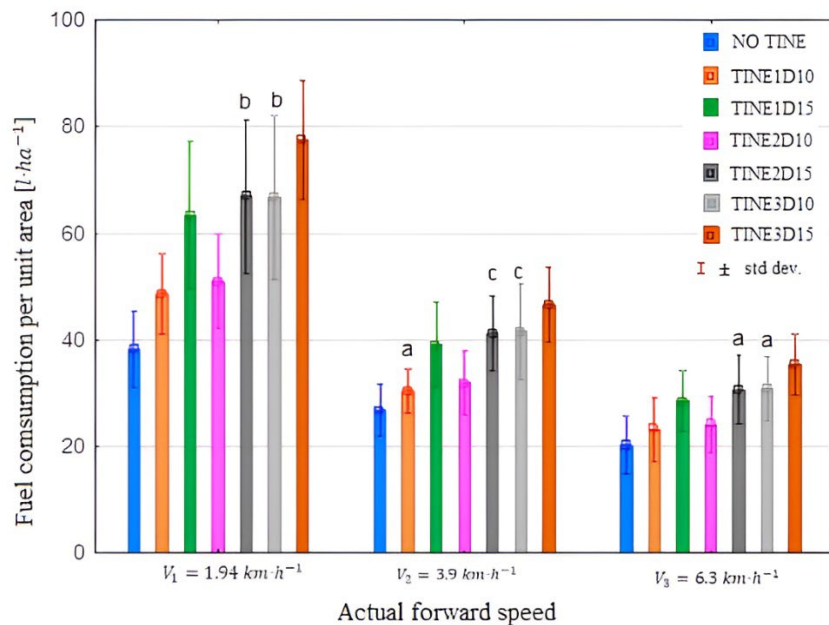


Figure 8. Effect of tines settings on the fuel consumption per unit area during ploughing ($L \cdot ha^{-1}$). Means followed by the same letter are not significantly different according to the Tukey test ($p \leq 0.05$)

Changing the forward speed from $V_1 = 1.94 \text{ km} \cdot \text{h}^{-1}$ to $V_3 = 5.70 \text{ km} \cdot \text{h}^{-1}$ resulted in an almost threefold (2.94) increase in ploughing area efficiency. This resulted in the decrease in fuel consumption per unit area by $17.96 \text{ L} \cdot \text{ha}^{-1}$ (NO TINE), $25.41 \text{ L} \cdot \text{ha}^{-1}$ (TINE1D10), $34.51 \text{ L} \cdot \text{ha}^{-1}$ (TINE1D15), $26.88 \text{ L} \cdot \text{ha}^{-1}$ (TINE2D10), $36.29 \text{ L} \cdot \text{ha}^{-1}$ (TINE2D15), $35.77 \text{ L} \cdot \text{ha}^{-1}$ (TINE3D10) and $42.07 \text{ L} \cdot \text{ha}^{-1}$ (TINE3D15).

Changing the working depth of the chisel tine from 0.10 to 0.15 m resulted in the increase: for two-heart type chisel spikes by $14.65 \text{ L} \cdot \text{ha}^{-1}$, $8.62 \text{ L} \cdot \text{ha}^{-1}$, $5.30 \text{ L} \cdot \text{ha}^{-1}$, for straight type chisel spikes by $15.93 \text{ L} \cdot \text{ha}^{-1}$, $9.38 \text{ L} \cdot \text{ha}^{-1}$, $6.52 \text{ L} \cdot \text{ha}^{-1}$, and for duck foot type chisel spikes by $10.79 \text{ L} \cdot \text{ha}^{-1}$, $5.08 \text{ L} \cdot \text{ha}^{-1}$, $4.49 \text{ L} \cdot \text{ha}^{-1}$ for speeds V_1 , V_2 , V_3 , respectively.

Koniuszy and Kostencki (2015) compared fuel consumption per unit area and hourly ploughing efficiency using a reversible seven-furrow plough aggregated with a John Deere 8330 tractor. When cultivating fields of different area (26.00 ha, 12.74 ha and 3.22 ha), they found that ploughing efficiency decreased with the cultivation of smaller fields by $2.35 \text{ ha} \cdot \text{h}^{-1}$, $2.23 \text{ ha} \cdot \text{h}^{-1}$ and $1.64 \text{ ha} \cdot \text{h}^{-1}$, respectively. Fuel consumption increased by $14.7 \text{ L} \cdot \text{ha}^{-1}$, $15.0 \text{ L} \cdot \text{ha}^{-1}$ and $18.0 \text{ L} \cdot \text{ha}^{-1}$, respectively. Memon et al., (2013) and Safari and Gazor (2014) pointed out a strong correlation between fuel consumption and ploughing depth. Increasing the working depth by every 0.01 m can cause an increase in fuel consumption of 0.5 to $1.5 \text{ L} \cdot \text{ha}^{-1}$, depending on the type of soil cultivated (Moitzi et al., 2006).

The Tukey test shows that in the tested soil layers of 0.20-0.25 m and 0.25-0.30 m, the average bulk densities of the soil determined for the test variants show statistically significant differences in relation to the control measurements. However, the bulk density in the soil layer of 0.30-0.35 m measured for variants TINE2D10 and TINE2D15 does not show significant differences in relation to the control measurement. An anomaly in this soil layer is the TINE3D15 test variant, which does not show significant differences in relation to the control measurement at the 0.25-0.30 m level. For the tested soil layers, i.e. 0.20-0.25 m and 0.25-0.30 m, the highest bulk densities for control measurements were found, $1.89 \text{ g} \cdot \text{cm}^{-3}$ and $1.83 \text{ g} \cdot \text{cm}^{-3}$, respectively. In contrast, at the soil layer of 0.30-0.35 m for variant TINE2D10, the value was $1.82 \text{ g} \cdot \text{cm}^{-3}$ an increase in soil compaction was observed compared to the control sample (NO TINE) (Fig. 9).

Increasing the working depth of the chisel tines from 0.10 to 0.15 m resulted in a change in soil bulk density: for two-hearts type chisel spikes by $0.10 \text{ g} \cdot \text{cm}^{-3}$, $0.07 \text{ g} \cdot \text{cm}^{-3}$ and $0.17 \text{ g} \cdot \text{cm}^{-3}$, for straight type chisel spikes by $0.12 \text{ g} \cdot \text{cm}^{-3}$, $0.06 \text{ g} \cdot \text{cm}^{-3}$ and $0.17 \text{ g} \cdot \text{cm}^{-3}$, and for duck foot type chisel spikes by $0.02 \text{ g} \cdot \text{cm}^{-3}$, $0.06 \text{ g} \cdot \text{cm}^{-3}$ and $0.34 \text{ g} \cdot \text{cm}^{-3}$, respectively for soil layers of 0.20-0.25 m, 0.25-0.30 m and 0.30-0.35 m.

Tsimba et al., (1999) demonstrated that soil bulk density increases with depth in the soil profile. This is caused by the decreasing content of organic matter and plant roots. In addition, the weight of the topsoil compacts the lower parts of the soil profile. The studies confirmed this hypothesis. The highest density was found in the topsoil layer, while the lowest density was found in the subsoil layer. In addition, the weight of the topsoil compacts the lower parts of the soil profile. The studies confirmed the above thesis. The highest soil bulk density was measured at the lowest soil level studied, i.e. 0.3-0.35 m below the field surface. During traditional ploughing, the highest soil compaction was measured in the upper part of the topsoil layer, and it decreases deeper into the soil profile (within the tested range). This is caused by the tractor, whose single pair of wheels moves in the furrow. Kasap (2001) and Boydas and Turgut (2007) demonstrated that soil bulk density decreases with increasing forward

speed. This is due to the shorter contact time of the wheels with the soil at a given location and, consequently, shorter kneading time. However, these changes are not statistically significant ($p > 0.05$). The results of the study show that the interaction between the type of working elements, their working depth and the forward speed of the aggregate is not statistically significant ($p > 0.05$). An increase in the forward speed of the aggregate resulted in the decrease in bulk density, but these changes were marginal.

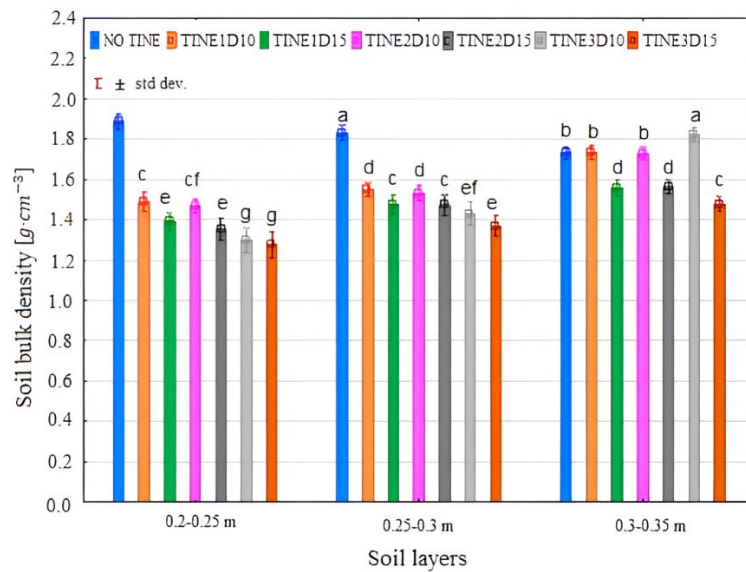


Figure 9. Effect of tines settings on the soil bulk density ($\text{g}\cdot\text{cm}^{-3}$). Means followed by the same letter are not significantly different according to the Tukey test ($p \leq 0.05$)

Conclusion

1. The use of a modernized plough for soil cultivation resulted in the significant increase in fuel consumption per unit area for all test variants compared to the control measurements (NO TINE). The largest increase (expressed as average fuel consumption per unit area) of approximately 102% was recorded for duck foot type chisel spikes at the working depth of 0.15 m (TINE3D15) and the forward speed of $V_1 = 1.94 \text{ km}\cdot\text{h}^{-1}$. The smallest difference, i.e. approx. 20%, was found for two-heart chisel spikes at the depth of 0.1 m (TINE2D10) at a forward speed of $V_3 = 5.70 \text{ km}\cdot\text{h}^{-1}$.
2. The use of two-heart type chisel spikes and straight type chisel spikes at the depth of 0.10 m caused damage to the plough pan at 2/3 of its thickness, without changing the physical properties of the soil below the working depth. Using this working depth of this chisel spikes does not eliminate the negative impact of the plough pan.
3. As a result of the work of chisel tines at the depth of 0.10 m, equipped with duck foot type chisel spikes, secondary soil compaction occurs below the working depth. This is

caused by their leading edges, which affect the soil in a similar way to a ploughshare. The soil bulk density shows statistically significant increases compared to the control measurement (NO TINE).

4. Using a modernized plough allows two energy-intensive operations – ploughing and subsoiling – to be combined in a single pass. This leads to the reduction in the energy required for tillage and a reduction in soil compaction, which is caused by a number of factors, including the movement of heavy vehicles across the field.

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WPLYW MODERNIZACJI PŁUGA NA ZUŻYCIE PALIWA PODCZAS ORKI I GĘSTOŚĆ OBJĘTOŚCIOWA PODŁOŻA

Streszczenie. Niniejsze badanie ma na celu rozwiązanie problemu nadmiernego zagęszczenia gleby w warstwie podglebia, spowodowanego ruchem i pracą maszyn rolniczych, poprzez modernizację konstrukcji pługa, łączącą dwie operacje o wysokim zapotrzebowaniu na energię: orkę i głębosowanie. Celem badania była modernizacja i udoskonalenie konstrukcji pługa lemieszowego poprzez dodanie dodatkowej ramy (zębów o zwiększonej wytrzymałości), na której zamontowano elementy robocze (zab dłutowy prosty, zab dłutowy dwusercowy, zab dłutowy typu „gęsia stopka”). Efektem modernizacji pługa było zniszczenie podeszwy płużnej, co prowadziło do zmniejszenia gęstości objętościowej gleby w warstwie podglebia. Natomiast w przypadku zastosowania zębów z zębem dłutowym typu „gęsia stopka” (sweep), zaobserwowano wzrost gęstości objętościowej gleby w warstwie poniżej głębokości roboczej narzędzia. Modernizacja pługa spowodowała wzrost zużycia paliwa na jednostkę powierzchni podczas orki w stosunku do powierzchni uprawianej. Zastosowanie zmodernizowanego pługa pozwala na połączenie dwóch energochłonnych operacji – orki i głębosowania – w jednym przejeździe.

Słowa kluczowe: podeszwa płużna, gęstość objętościowa, zużycie paliwa