PAN POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2024.151556
2024, No. 62 (VII–IX): 88–96

The productivity of selected soybean cultivars grown using various cultivation methods

Jerzy Księżak, Jolanta Bojarszczuk*

Institute of Soil Science and Plant Cultivation – State Research Institute, Czartoryskich 8, 24-100 Puławy, Poland

* Corresponding author

RECEIVED 15.01.2024 ACCEPTED 24.04.2024 AVAILABLE ONLINE 18.10.2024

Abstract: Soybean is an important legume crop globally due to its rich protein, oil content, and functional components. The purpose of this study was to evaluate the yield of selected soybean cultivars depending on cultivation methods. The three-year field experiment, conducted from 2018 to 2020 at the Agricultural Experimental Station in Kępa-Puławy, Osiny farm (Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy), investigated these variations. The first experimental factor was the soil cultivation method: A – conventional tillage, B – reduced tillage, and C – strip tillage. The second variable was soybean cultivar: 'Aldana' and 'Merlin'. The soybean cultivars were selected for their differing maturity rates: 'Aldana' (000) is an early cultivar, while 'Merlin' (000++) semi-late cultivar. The field experiment utilised a split-plot design on Luvisol soil with sandy loam texture, belonging to a good rye complex, class IIIb–IVa, and was replicated four times. The study showed that the productivity (seed and protein yield) of the 'Merlin' cultivar grown in the central-eastern part of Poland was approximately 8% higher than that of the 'Aldana' cultivar. The cultivation method had a relatively minor influence on soybean yield, the content of selected nutrients, morphological features, and elements of the yield structure. The soil in strip-tillage method was more compact than the soil cultivated with a plough. After harvesting soybeans at a depth of 30, and 40 cm, the compactness of soil in strip-tillage or with reduced tillage was much lower than in spring, highlighting a positive effect of soybean cultivation on loosening the arable layer.

Keywords: cultivar, *Glycine max.* (L.) Merrill, tillage method, yield, yield components

INTRODUCTION

Soybean [*Glycine max* (L.) Merrill] is one of the most valuable, and important legume crop cultivated in the world. Its seeds characterised the high nutritional value, which contain about 40% of protein with a favourable amino acid composition, 18–24% fat, and only 5–8% crude fibre (James and Yang, 2016; Luboiński and Markowicz, 2017; Kotecki and Lewandowska, 2020).

Soil tillage methods can be classified in descending order in terms of their propensity to facilitate soil erosion as follows: conventional tillage, reduced tillage, and no tillage (Knapen *et al.*, 2007). According to Małecka *et al.* (2012), soil cultivation methods used in Poland can be categorised into two groups: conventional tillage, and conservation tillage, which includes shallow cultivation or direct drilling. Agronomic practices that replace the plough with implements that do not turn the soil over offer an alternative for agricultural producers. Pittelkow *et al.* (2015) proved that no-tillage performs best in dry climate conditions, with crop yields often equal to or higher than those obtained with conventional tillage. Dzienia, Zimny and Weber *et al.* (2006) stated that the no-tillage method can reduce energy and labour costs by about 35%.

According to other authors, the decrease in yield with the zero-tillage method may be influenced by meteorological conditions (Carr, Martin and Horsley, 2009; Soane *et al.*, 2012; Santín-Montanyá *et al.*, 2014) and an increase in bulk density, especially in the first years of the study (Dzienia, Zimny and Weber, 2006; Małecka, Blecharczyk and Dobrzeniecki, 2007). This may inhibit and reduce field emergence and root system development, leading to a slower increase in aboveground plants biomass and the accumulation of components in comparison to conventional tillage (Soane *et al.*, 2012).

The conventional method positively affects the complex of soil properties (Page *et al.*, 2020). Reduced soil tillage allows for reduced inputs while achieving similar or even higher crop yields in comparison to conventional tillage. Gozubuyuk, Sahin and Celik (2020) stated that using reduced tillage, fuel using was 3.5 times lower compared to conventional tillage method. However, reduced tillage may result in higher CO_2 emissions when plant residues are heavily mineralised on the soil surface (Giacomo *et al.*, 2014).

The strip-till method follows the principles of conservation agriculture, with approximately 50–75% of the soil covered by plant residues (Morrison, 2002; Morris *et al.*, 2010; Townsend, Ramsden and Wilson, 2016). Using a strip-till one-pass technique, seeds, and fertilisers are applied during the loosening of soil strips. Moreover, other agrotechnical practices, such as plant protection treatments and intercrops sowing, can be performed simultaneously. This approach is more economical and reduces the environmental pressure of field crop production (Morrison and Sanabria, 2002).

The purpose of the research was to determine production effects of two soybean cultivars depending on cultivation methods: conventional tillage, reduced tillage, and strip tillage. The study evaluated the influence of the tillage system on yield, its components, and certain quality characteristics of soybean seeds.

MATERIALS AND METHODS

A three-year experiment was conducted from 2018 to 2020 at the Agricultural Experimental Station in Kępa-Puławy, Osiny farm (Lubelskie Voivodeship, Poland), part of the Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy. The experimental site is located in a moderate continental climatic zone. The field experiment followed a split-plot design on Luvisol soil with sandy loam texture classes, belonging to a good rye complex, class IIIb–IVa, and was replicated four times.

The first experimental factor was the soil cultivation method: A – conventional tillage, B – reduced tillage, and C – strip tillage. The second factor was soybean cultivar: 'Aldana' and 'Merlin'. Soybean cultivars with various earliness were used in the trails: 'Aldana' (000) early cv. (125–130 days of vegetation), 'Merlin' (000++) semi-late cv. (127–132 days of vegetation).

In the experiment, the forecrop in 2018–2019 was spring wheat, while in 2020 it was winter wheat. Row spacing was 24 cm, sowing rate was 80 germinating seeds per 1 m^2, and the sowing depth was 3–4 cm. The plots for sowing were 20 m^2 in size, and for harvest they were 15 m^2. The soil pH (in 1 M KCl) ranged from 5.2 to 5.9, depending on the study year. The content of available forms of potassium was 5.0–10.7 mg $K\cdot kg^{-1}$ soil, phosphorus 13.1–28.7 mg $P\cdot kg^{-1}$ soil, and magnesium 13.0–15.9 mg $Mg\cdot kg^{-1}$. The content of mineral N in the soil layer (0–60 cm depth) was 40–62 $kg\cdot ha^{-1}$. Mineral fertilisation was applied before sowing at the rates of P_2O_5 – 50 $kg\cdot ha^{-1}$, and K_2O – 90 $kg\cdot ha^{-1}$. Soybean was sown at the beginning of May.

The selection of cultivating machines and tools varied and depended on the tillage system. In the conventional and reduced tillage methods (A and B), after harvesting the forecrop (depending on the year of the study: winter or spring wheat), a shallow cultivation (stubble) was performed using a disc harrow to a depth of 5–6 cm. In autumn, in the conventional tillage (A) ploughing was carried out using a reversible plough to a depth of 25 cm. In spring, in the conventional tillage (A), the harrowing was carried out. Then, in both the conventional tillage (A) and reduced tillage (B), a shallow cultivation (stubble) was carried out with a disc harrow to a depth of 5–6 cm. Sowing was performed in the conventional tillage and reduced tillage (A and B) using the Kockerling Ultima seeder made by Deutz Fahr, while in the strip-tillage method (C), sowing was carried out directly into the stubble using the MZURI seeder by VALTRA.

To control weed infestation, Klinik Free 360 SL (at a rate 5.0 $dm^3\cdot ha^{-1}$, active substance: glyphosate 360 $g\cdot dm^{-3}$, 30.56%, NUFARM) was applied in autumn on the strip-tillage, while Vival 360 SL (at a rate 4.0 $dm^3\cdot ha^{-1}$, active substance: 360 $g\cdot dm^{-3}$ gliphosate, Helm AG, Hamburg, Germany) was applied to the other plots in spring. During the vegetation period, Corum 502.4 SL (at a rate 1.25 $dm^3\cdot ha^{-1}$, active substance: 480 $g\cdot dm^{-3}$ bentazone, and 22.4 $g\cdot dm^{-3}$ imazamox; BASF, Luwigshafen, Germany) + Dash HC (adjuvant) (at the rate 1.0 $dm^3\cdot ha^{-1}$), and Supero 05EC (at the rate 1.2 $dm^3\cdot ha^{-1}$, active substance: 50 $g\cdot dm^{-3}$ chizalofop-P-ethyl, Sharda CropChem Ltd., India were applied using a KFMR Krukowiak sprayer. Moreover, Dithane NeoTec 75 WG (at the rate 2 $kg\cdot ha^{-1}$, active substance: mancozeb 750 $g\cdot kg^{-1}$ (75%) was applied. Seeds were inoculated with a bacterial culture, Nitragina (IUNG-PIB, PL). The plant harvest was carried out at the full maturity stage using a Wintersteiger harvester, with maturity dates shown in Table 1.

The N content in the dry weight of seeds was measured using flow analysis with spectrometric detection. Total protein was determined by the Kjeldahl distillation method (Kjeldahl, 1883) after mineralisation in sulphuric acid, while crude fat content was measured using the Soxhlet's method (Soxhlet, 1879).

Table 1. Date of sowing, full maturity of soybean cultivars and length of growing seasons in 2018–2020

Specification	Year of the study					
	2018		2019		2020	
Soybean cultivar	'Aldana'	'Merlin'	'Aldana'	'Merlin'	'Aldana'	'Merlin'
Date of sowing	14.04		24.04		07.05	
Date of full maturity	12.09	12.09	17.09	27.09	8.10	16.10
Length of growing season (days)	153	153	147	157	155	163

Source: own study.

Crude fibre (CF) was analysed using the enzymatic-weight method (Nogala-Kałucka (ed.), 2016).

Right before harvest, ten plants were collected from each plot to determine morphological traits and structural components of soybean yield: including the number of pods per plant, the number and weight of seeds per plant, the number of seeds per pod, dry matter of aboveground parts of plants, and the number of nods. Moreover, dry matter of roots was measured. The evaluation of soybean nodulation was determined in 2018 and 2019.

In 2019, soil compactness (in MPa) was measured as an indicator of penetration resistance. An Eijkelkamp penetrologger with a built-in data recorder was used to measure every 1 cm to a depth of 60 cm. Soil compactness measurements were performed in spring before sowing and in autumn after the soybean harvest. For the calculation of soil compactness, the average value from five repetitions was taken for each plot and tested depths.

In 2018–2020, the electrical conductivity test was carried out. For the test, 50 randomly selected seeds from each replication were soaked in 300 cm^3 deionised water in beakers and kept in a thermostat at 20 ±1°C for 24 hours. After stirring the liquid, the electrical conductivity of the solution with the seeds was measured using an Elmetron CC-551 microcomputer conductometer. The results were recorded in $\mu S \cdot cm^{-1} \cdot g^{-1}$.

The ranges of the hydrothermal index values, and its interpretation were determined depending on the value of k:
- extremely dry – $k \leq 4$,
- very dry – $0.4 < k \leq 7$,
- dry – $0.7 < k \leq 0$,
- quite dry – $1.0 < k \leq 1.3$,
- optimal – $1.3 < k \leq 6$,
- moderately humid – $1.6 < k \leq 0$,
- humid – $2.0 < k \leq 5$,
- very humid – $2.5 < k \leq 0$,
- extremely humid – $k > 3.0$.

The obtained meteorological data allowed to determine the humidity characteristics of individual months during the growing seasons over three years. According to the Selyaninov hydrothermal index (k), the dry months were: April, June, and August in 2018; June and July in 2019; and April and July 2020. The wettest months according to the Selyaninov index were May in 2019, and May and June in 2020 (Tab. 2).

The obtained results were statistically analysed using the variance analysis with Statistica v.10.0 software (StatSoft, Poland). Tukey's multiple comparison test was used to compare the differences between the means for the soil cultivation method, while confidence intervals for the means of *LSD* ($\alpha = 0.05$) were used.

Table 2. Characteristic of vegetation periods (2018–2020) on the base of Selyaninov hydrothermal index (k)

Month	Year of the study					
	2018		2019		2020	
	k	hydrothermal conditions	*k*	hydrothermal conditions	*k*	hydrothermal conditions
April	0.73	dry	1.24	quite dry	0.48	very dry
May	1.12	quite dry	2.14	humid	3.30	extremely humid
June	0.68	very dry	0.60	very dry	3.45	extremely humid
July	1.01	quite dry	0.58	very dry	0.87	dry
August	0.43	very dry	1.38	optimal	1.13	quite dry
September	1.02	quite dry	1.36	optimal	2.33	humid

Source: own study.

The sum of mean daily temperatures (°C) and the sum of precipitation (mm) for years 2018–2020 were calculated using data from a weather station located close to experimental fields, belonging to the Institute of Soil Science and Plant Cultivation – State Research Institute.

The characteristics of thermal and precipitation conditions over three growing seasons were described using Selyaninov's hydrothermal coefficient (Skowera, 2014; Selyaninov, 1930 cited by Radomski, 1973, p. 32), also known as the water security coefficient or conventional humidity balance (Tab. 2). This indicator (k) determines the ratio of the sum of precipitation to the sum of average daily air temperatures in a given period:

$$k = \frac{10P}{\sum t} \tag{1}$$

where: P = monthly precipitation total (mm), $\sum t$ = sum of daily average temperature in month > 0°C.

RESULTS AND DISCUSSION

Soybean yields and structural yield components of two cultivars were significantly influenced by the varied course of weather conditions (temperature, total precipitations, and its distribution) during the growing season and cultivation methods used in soybean production. The effect of weather conditions on soybean seed yields is confirmed by other authors (Fecák, Šariková and Černý, 2010; Gawęda *et al.*, 2020; Chețan *et al.*, 2022; Księżak and Bojarszczuk, 2022). The most favourable conditions affecting soybean productivity occurred in the third year of research (2020), with seed and protein yields being 80% higher than in 2019 and approximately 50% higher than in 2018 (Tabs. 3, 4). The tillage method in years with lower total precipitation (2018 and 2019) had no significant effect on soybean productivity. Only in 2020 did soybean grown using the conventional tillage method yield better (Tabs. 3, 4). Barrios *et al.* (2006), Lopes *et al.* (2007),

Table 3. Yield and weight of 1000 seeds of soybean depending on cultivar and cultivation method

Cultivation method	Cultivar	Seeds yield ($Mg \cdot ha^{-1}$) in				Weight of 1000 seeds (g) in			
A	'Aldana'	2.02*	1.84	3.53	2.46	143.8	146.0	159.6	149.8
	'Merlin'	2.36	1.88	3.65	2.63	146.4	133.9	152.7	144.3
	mean	2.19	1.86	3.59	–	145.1	140.0	156.2	–
B	'Aldana'	1.96	1.76	3.14	2.29	142.7	144.8	161.8	149.8
	'Merlin'	2.33	1.91	3.30	2.51	145.0	136.7	156.2	146.0
	mean	2.14	1.84	3.22	–	143.8	140.7	159.0	–
C	'Aldana'	2.05	1.81	3.15	2.34	146.2	144.4	161.0	150.3
	'Merlin'	2.44	1.88	3.22	2.51	148.8	137.6	157.9	148.1
	mean	2.24	1.84	3.18	–	147.5	141.0	159.4	–
Mean		**2.19**	**1.85**	**3.33**	**–**	**145.5**	**140.6**	**158.2**	**–**
LSD (α = 0.05)									
– CM	–	n.s.	0.01	0.05	–	0.03	n.s.	1.35	–
– CR		0.34**	0.03	0.05		0.41	1.54	0.05	
– CR/CM		n.s.	0.04	n.s.		n.s.	1.70	1.24	
– CM/CR		n.s	0.04	n.s.		n.s.	2.47	1.93	

Explanations: A = conventional tillage, B = reduced tillage, C = strip tillage, CM = cultivation method; CR = cultivar, * mean at $p \leq 0.05$; ** significant at $p \leq 0.05$ according to Tukey's honestly significant difference (*HSD*) test; n.s. = non-significant.
Source: own study.

Table 4. Yield and content of protein in soybean seeds depending on variety and cultivation method

Cultivation method	Cultivar	Protein yield ($kg \cdot ha^{-1}$) in				Protein content ($g \cdot kg^{-1}$) in			
A	'Aldana'	686*	598	1137	807	294	325	322	314
	'Merlin'	797	614	1184	865	296	326	324	316
	mean	741	606	1160	–	295	326	323	–
B	'Aldana'	664	579	1015	753	295	329	323	316
	'Merlin'	787	628	1075	830	296	329	326	317
	mean	726	603	1045	–	296	329	324	–
C	'Aldana'	692	618	1028	779	296	329	326	317
	'Merlin'	808	604	1052	821	302	328	327	319
	mean	750	611	1040	–	299	328	326	–
Mean		**739**	**607**	**1082**	**–**	**297**	**328**	**325**	**–**
LSD (α = 0.05)									
– CM	–	10.85**	n.s.	14.28	–	2.71	0.84	n.s.	–
– CR		3.89	2.53	10.76		1.33	n.s.	n.s.	
– CR/CM		n.s.	4.62	11.02		n.s.	n.s.	n.s.	
– CM/CR		n.s.	12.92	14.60		n.s.	n.s.	n.s.	

Explanations as in Tab. 3.
Source: own study.

Lança Rodrígues *et al.* (2009), Stipešević *et al.* (2009), Monsefi *et al.* (2014), Adamič and Leskovšek (2021) and Cheţan *et al.* (2022) found significantly higher yields in soybean crops under conventional tillage compared to no-tillage methods. According to Lança Rodrígues *et al.* (2009), lower yield values under no-tillage conditions occurred because of the lower numbers of grains per pod and pods per plant.

While other authors, such as Hosseini *et al.* (2016), reported an increase in soybean yield under no-till conditions, the beneficial effect of soybean cultivation in strip-tillage was also documented by Farmaha *et al.* (2011) and Potratz *et al.* (2020).

Farmaha *et al.* (2011) showed that strip-till cultivation allows for higher soybean yields than no-till cultivation. Research by Vyn, Opoku and Swanton (1998) confirmed that strip-till cultivation provided 29% higher soybean yields compared to no-tillage. Potratz *et al.* (2020) proved that the highest yields of soybean seeds are achieved with strip-tillage at a row spacing of 38 cm.

Vita de *et al.* (2007) stated that the benefits of no-till can be noted in warm years with lower precipitation during vegetation period. Dick and Doren van (1985) noted that soybean production using a no-tillage soil method is often less beneficial in poorly drained soils, partly due to cooler and wetter soil conditions at planting (Meese *et al.*, 1991). Such soil conditions can lead to slower soybean germination and emergence making the seedlings more vulnerable to diseases.

Karunakaran and Behera (2016) reported that soybean seed yields under no-tillage were similar to those achieved with conventional methods. Gawęda *et al.* (2020) found that the tillage method significantly influenced soybean yield as well as the protein and fat content in seeds. Under the plough tillage method, seed yield was 10.3% higher compared to that obtained under no-tillage.

In our study, the lowest amount of protein was found in soybean seeds grown in a year with unfavourable rainfall distribution (2018) and a higher amount in the other two years of the study (Tab. 4). The cultivars included in the study contained similar amounts of fat and fibre. Regardless of agroecological conditions and cultivation method, the 'Merlin' cultivar yielded better than the 'Aldana' cultivar (Tabs. 3, 4). Moreover, in 2018, most fat and fibre were accumulated in the seeds (Tab. 5). Fecák, Šariková and Černý (2010) found that seed protein and oil were highly significantly affected by weather conditions.

In the study by Adamič and Leskovšek (2021), significant differences between the tillage methods were observed for crude protein content, while no significant differences were found for crude fat, fibre, and ash. Protein content in legumes can be influenced by such factors as cultivar, climatic conditions, and soil tillage methods (Szwejkowska, 2005; Chetan *et al.*, 2016). Cober *et al.* (2005) reported that protein content was also influenced by plant density.

A previous study by the authors showed that soybean seeds grown under conditions of limited precipitation accumulated 9% more protein than those grown in more favourable conditions (Księżak and Bojarszczuk, 2022). Bertheau and Davison (2021) reported that the highest fibre content was observed in years with high temperatures and moderate precipitation during the soybean vegetation period. The beneficial effect of strip-till cultivation on the quality of soybean seeds was demonstrated by Farmaha *et al.* (2011) and Redondo-Cuenca, Villanueva-Suárez and Mateos-Aparicio (2008). In their research, soybean seeds grown in strip-till contained more protein compared to no-till.

The assessed cultivation methods had relatively little effect on the morphological features, elements of the yield structure, and the concentration of more important nutrients in the seeds of both cultivars (Tabs. 6, 7). Moreover, the 'Merlin' cultivar was characterised by more favourable elements of the yield structure, while the 'Aldana' cultivar produced seeds of greater weight than the 'Merlin' cultivar.

In the study by Lança Rodrígues *et al.* (2009), the highest weight of thousand soybean grains was observed in conventional soil tillage. Similar results were reported by Lopes *et al.* (2007) and Adamič and Leskovšek (2021). Opposite results were reported by Pedersen and Lauer (2003), where a bigger seed mass was noted for the no-tillage method. Adamič and Leskovšek

Table 5. Total crude fat and crude fibre content in seeds dry matter depending on soybean cultivar and cultivation method (mean for 2018–2020)

Cultivation method	Cultivar	Crude fat	Crude fibre
A	'Aldana'	244*	56.6
	'Merlin'	246	55.5
	mean	245	56.1
B	'Aldana'	242	56.3
	'Merlin'	245	55.9
	mean	244	56.1
C	'Aldana'	244	57.1
	'Merlin'	244	55.7
	mean	244	56.4
LSD (α = 0.05)			
– CM	–	n.s.	n.s.
– CR		n.s.	n.s.
– CR/CM		n.s.	n.s.
– CM/CR		n.s.	n.s.

Explanations as in Tab. 3.
Source: own study.

Table 6. Seeds number per pod and number of pod per plant depending on soybean cultivar and cultivation method

Cultivation method	Cultivar	Number of seeds per pod (units)	Number of pods per plant (units)
A	'Aldana'	1.90*	18.3
	'Merlin'	1.99	21.5
	mean	–	–
B	'Aldana'	1.91	18.6
	'Merlin'	1.98	20.9
	mean	–	–
C	'Aldana'	1.89	18.3
	'Merlin'	2.00	21.1
	mean	–	–
LSD (α = 0.05)			
– CM	–	n.s.	n.s.
– CR		n.s.	n.s.
– CR/CM		n.s.	n.s.
– CM/CR		n.s.	n.s.

Explanations as in Tab. 3.
Source: own study.

Table 7. Seed number and weight per plant depending on the soybean cultivar and cultivation method

Cultivation method	Cultivar	Number of seeds per plant (units)	Weight of seeds per plant (g)
A	‘Aldana’	29.9*	6.09
	‘Merlin’	34.6	6.41
	mean	–	–
B	‘Aldana’	32.4	5.81
	‘Merlin’	33.3	6.18
	mean	–	–
C	‘Aldana’	31.5	5.74
	‘Merlin’	33.5	6.05
	mean	–	–
LSD (α = 0.05)			
– CM	–	1.12**	0.12
– CR		0.59	0.25
– CR/CM		0.67	n.s
– CM/CR		0.68	n.s

Explanations as in Tab. 3.
Source: own study.

(2021) found the greatest number of pods per plant in the conventional method, while the lowest number was observed in the conservation method. These authors observed also the greatest number of pods per unit area (m^{-2}) in the conventional method, with significantly lower pod numbers in the conservation and no-tillage methods. Lança Rodrígues (2009) also found that conventional and reduced soil tillage methods showed greater number of pod per plant compared to the no-tillage method.

The tillage method had no significant effect on the number of nodules per plant for the roots (Tab. 8). The evaluated cultivars produced similar weight, number of nodules on the root system, and the tillage method used had a relatively small effect on these features. In 2019, the ‘Merlin’ cultivar produced more nodules, regardless of the cultivation method (Tab. 8). Moreover, in this year, the plants of this cultivar were characterised by a much greater weight of the root system than the ‘Aldana’ cultivar, while in the next two years, these differences were small (Tab. 9). Furthermore, the cultivation method resulted in slight differences in the root system of both soybean cultivars.

In the study of Adamič and Leskovšek (2021), the tillage method had a significant impact on the number of nodules per plant for the tap root. The highest nodule production for the tap root of the soybean plants was noted for the conventional and no-tillage methods. Matsuo *et al.* (2019) also noted a more number of nodes on soybean crops cultivated under the conventional soil method.

These results are in line with the study by Kombiok and Buah (2013), where the numbers of nodules on the roots increased with increasing soil tillage depth. Conversely, Hanhur *et al.* (2020) reported greater nodule development on soybean cultivated in medium-shallow tilled soil compared to medium-deep tilled soil.

Table 8. Evaluation of soybean nodulation depending on cultivar and cultivation method

Cultivation method	Dry weight (g)				Number of nod (unit per plant)			
	Aldana		Merlin		Aldana		Merlin	
	2018		2019		2018		2019	
A	–	0.18	0.40	–	–	6.25	10.3	–
B	–	0.10	0.20	–	0.50	5.75	7.30	–
C	0.10	0.03	0.40	0.04	1.30	2.00	39.8	2.00
Mean	**–**	**0.10**	**0.30**	**0.04**	**0.60**	**4.67**	**19.1**	**2.00**

Explanations: A, B, and C as in Tab. 3.
Source: own study.

Table 9. Weight of root system depending on cultivar and cultivation method in 2018–2020

Cultivation method	Root system weight		
	dry weight (g)		mean
	‘Aldana’	‘Merlin’	
2018			
A	4.8*	12.8	8.8
B	4.3	7.3	5.8
C	4.6	5.9	5.3
Mean	**4.6**	**8.7**	–
LSD (α = 0.05)			
– CM	–	0.22	–
– CR		0.25	
– CR/CM		0.28	
– CM/CR		0.27	
2019			
A	1.81	2.36	2.1
B	1.43	1.97	1.7
C	1.47	1.65	1.6
Mean	**1.57**	**1.99**	–
LSD (α = 0.05)			
– CM	–	0.03	–
– CR		0.08	
– CR/CM		0.08	
– CM/CR		0.05	
2020			
A	4.96 4.82	4.56	4.76
B		4.41	4.61
C	4.73	4.13	4.43
Mean	**4.74**	**4.37**	–
LSD (α = 0.05)			
– CM	–	0.19**	–
– CR		0.20	
– CR/CM		0.23	
– CM/CR		0.22	

Explanations as in Tab. 3.
Source: own study.

Adamič and Leskovšek (2021) reported that tillage methods they analysed (conventional, conservation, and no-tillage) had a significant influence on soybean shoot and root dry matter production. The greatest dry matter of root was also noted for the soybean plants grown under the conventional soil method (6.2 g per plant).

According to Adamič and Leskovšek (2021), tillage methods had significant effects on the dry nodule weight per plant, with the conventional method showing significantly higher values than the no-tillage method. In their study, tillage methods also had significant effects on the dry nodule mass per square meter, which was greatest for the conventional method and significantly lower for the no-tillage method.

Hanhur *et al.* (2020) reported that the main factors influencing the number and mass of nodules are soil moisture, gas exchange between the soil and the environment, and soil temperature. Ferreira *et al.* (2000) presented that reduced tillage methods improved soil biological characteristics and plant growth. These findings confirm the study by Adamič and Leskovšek (2021), where shoot and root dry matter in the no-tillage method were significantly greater than the conservation tillage method.

The measurements of soil compactness carried out in spring and autumn showed that in both periods the soil cultivated in the strip-tillage method was more compact, while the soil cultivated in the plough method was the least compact (Fig. 1). The compactness of the soil changed depending on the depth and the cultivation method used. The obtained results indicate that in autumn, at a depth of 10 cm, the soil was more compact than in spring, especially in the conventional tillage method. After harvesting soybeans, at a depth of 20 cm, the compaction in the area with the full conventional tillage method significantly increased compared to that recorded in spring, and it significantly decreased in the soil cultivated using strip-tillage. Measurements taken at a depth of 30 and 40 cm in autumn indicate that the compactness of the soil where reduced tillage or strip-tillage was used was much lower. This confirms the beneficial effect of soybean on loosening the topsoil. At a depth of less than 40 cm in spring, the soil was characterised by similar compactness regardless of the cultivation method, and in autumn, the soil with strip-tillage was more compact.

Legumes with large, normally living cotyledons are good material for the electrical conductivity vigour test to indicate field emergence. In this trials, the electrical conductivity (*EC*) test showed the effect of soil cultivation methods on the *EC* of stagnation waters in soybean seeds (Tab. 10). The highest electrical conductivity of standing waters was observed in the soybean seeds grown under the strip-tillage method (mean for both cultivar – 12.3 $\mu S \cdot cm^{-1} \cdot g^{-1}$), while the lowest under the conventional tillage method (mean – 15.2 $\mu S \cdot cm^{-1} \cdot g^{-1}$). Similar results were obtained by Faligowska *et al.* (2016). In their study, the highest value of *EC* was noted in narrow-leaved lupine seeds grown under the no-tillage method. Moreover, those authors recorded that the *EC* test did not show any effect of irrigation and soil tillage methods on seed vigour.

Seed vigour determined by the conductometric method was mainly modified by the cultivar factor. Statistically significant differences in the *EC* values of the stagnation waters of the compared soybean cultivars ('Aldana' and 'Merlin') were found. The stagnation water of the 'Merlin' cultivar was characterised by a higher electrical conductivity than that of the 'Aldana' cultivar. This fact may be due to a decrease in the integrity of cell membranes in soybeans.

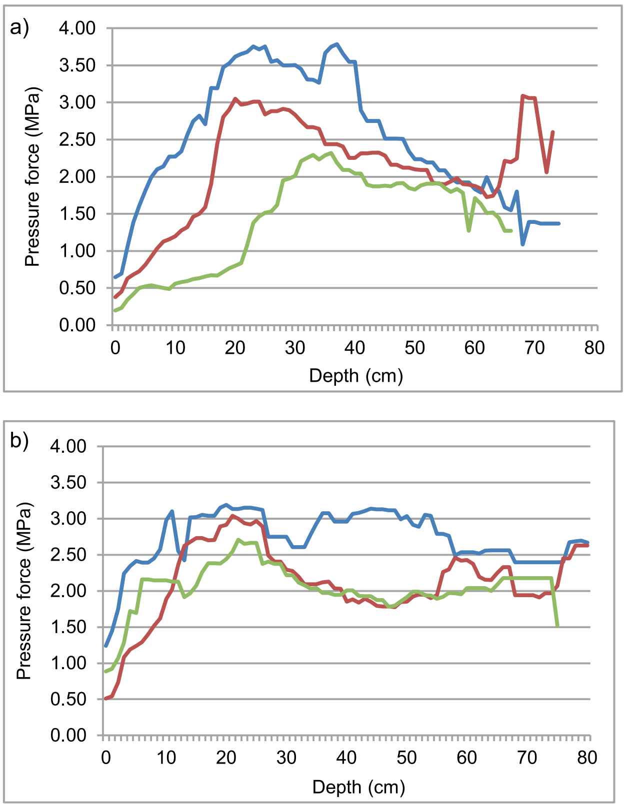

Fig. 1. Soil compactness measurements: a) spring; b) autumn; source: own study

Table 10. Electrical conductivity test ($\mu S \cdot cm^{-1} \cdot g^{-1}$) of soybean seeds depending on cultivars and soil tillage method

Cultivation method	Cultivar	Electrical conductivity test ($\mu S \cdot cm^{-1} \cdot g^{-1}$)			
		2018	2019	2020	mean
A	'Aldana'	11.8*	11.9	12.4	12.0
	'Merlin'	12.4	12.8	12.3	12.5
	mean	12.1	12.4	12.4	–
B	'Aldana'	12.4	13.3	13.5	13.1
	'Merlin'	13.1	14.0	13.7	13.6
	mean	12.8	13.7	13.6	–
C	'Aldana'	14.5	15.4	14.9	14.9
	'Merlin'	14.7	15.8	15.7	15.4
	mean	14.6	15.6	15.3	–
LSD (α = 0.05)					
– CM	–	0.11**	0.06	0.05	–
– CR		n.s.	0.04	0.01	
– CR/CM		n.s.	n.s.	n.s.	
– CM/CR		n.s.	n.s.	n.s.	

Explanations as in Tab. 3.
Source: own study.

CONCLUSIONS

The soybean productivity (seed and protein yield) of the 'Merlin' cultivar grown in the central-eastern part of Poland was approximately 8% higher than that of the 'Aldana' cultivar. The cultivation method had a relatively small effect on soybean yield, the content of selected nutrients, morphological features, and elements of the yield structure.

The soil cultivated using the strip-tillage method was more compact than the soil cultivated with the conventional tillage method. After harvesting soybean, at a depth of 30 and 40 cm, the compactness of the soil cultivated with strip-tillage or reduced tillage was much lower than in spring, indicating a beneficial effect of soybean on loosening the arable layer.

The 'Aldana' and 'Merlin' cultivars produced a similar number of nodules on the root system, while the tillage method used had a relatively small impact on these features. Seed vigour, determined by the conductometric method, was mainly influenced by the cultivar factor.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

REFERENCES

Adamič, S. and Leskovšek, R. (2021) "Soybean (*Glycine max* (L.) Merr.) growth, yield, and nodulation in the early transition period from conventional tillage to conservation and no-tillage systems," *Agronomy*, 11(12), 2477. Available at: https://doi.org/10.3390/agronomy11122477.

Barrios, M.B. *et al.* (2006) "Soil physical properties and root activity in a soybean second crop/maize rotation under direct sowing and conventional tillage," *Spanish Journal of Agricultural Research*, 4, pp. 355–362. Available at: https://doi.org/10.5424/sjar/2006044-212.

Bertheau, Y. and Davison, J. (2021) "Soybean in the European Union, status and perspective," in D. Krezhova (ed.) Recent trends for enhancing the diversity and quality of soybean products", London, UK: IntechOpen, pp. 3–47. Available at: https://doi.org/10.5772/18896.

Carr, P.M., Martin, G.B. and Horsley, R.D. (2009) "Impact of tillage on field pea following spring wheat," *Canadian Journal of Plant Science*, 89, pp. 281–288. Available at: https://doi.org/10.4141/CJPS08086.

Chetan, C. *et al.* (2016) "Research regarding the influence weed control treatments on production and qualitative indicators soybean cultivated in minimum tillage system," *Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture*, 73(2), pp. 170–175. Available at: https://doi.org/10.15835/buasvmcn-agr:11197.

Cheţan, F. *et al.* (2022) "Influence of soil tillage systems on the yield and weeds infestation in the soybean crop," *Land*, 11, 1708. Available at: https://doi.org/10.3390/land11101708.

Cober, E.R. *et al.* (2005) "Genetic improvement rates of short-season soybean increase with plant population," *Crop Science*, 45, pp. 1029–1034. Available at: https://doi.org/10.2135/cropsci2004.0232.

Dick, W.A. and Doren van, D.M. (1985) "Continuous tillage and rotation combinations effects on corn, soybean, and oat yields," *Agronomy Journal*, 77, pp. 459–465. Available at: https://doi.org/10.2134/agronj1985.00021962007700030023x.

Dzienia, S., Zimny, L. and Weber, R. (2006) "Najnowsze kierunki w uprawie roli i technice siewu [The latest trends in tillage and sowing technology]" *Fragmenta Agronomica*, 23(2), pp. 227–241.

Faligowska, A. *et al.* (2016) "Germination and vigour of narrow-leaved lupin seeds as the effect of irrigation of parent plants and cultivation in different soil tillage systems," *Polish Journal of Agronomy*, 24, pp. 3–8. Available at: https://doi.org/10.26114/pja.iung.276.2016.24.01.

Farmaha, B.S. *et al.* (2011) "No-till and strip-till soybean production with surface and subsurface phosphorus and potassium fertilization," *Agronomy Journal*, 103(6), pp. 1862–1869. Available at: https://doi.org/10.2134/agronj2011.0149.

Fecák, P., Šariková, D. and Černý, I. (2010) "Influence of tillage system and starting N fertilization on seed yield and quality of soybean *Glycine max* (L.) Merrill," *Plant Soil and Environment*, 56(3), pp. 105–110. Available at: https://doi.org/10.17221/201/2009-PSE.

Ferreira, M.C. *et al.* (2000) "Tillage method and crop rotation effects on the population sizes and diversity of bradyrhizobia nodulating soybean," *Soil Biology and Biochemistry*, 32(5), pp. 627–637. Available at: https://doi.org/10.1016/S0038-0717(99)00189-3.

Gawęda, D. *et al.* (2020) "Yield and economic effectiveness of soybean grown under different cropping systems," *International Journal of Plant Production*, 14, pp. 475–485. Available at: https://doi.org/10.1007/s42106-020-00098-1.

Giacomo, G. *et al.* (2014) "Measurements of soil carbon dioxide emissions from two maize agroecosystems at harvest under different tillage conditions," *The Scientific World Journal*, 2014, 41345. Available at: https://doi.org/10.1155/2014/141345.

Gozubuyuk, Z., Sahin, U. and Celik A. (2020) "Operational and yield performances and fuel-related CO_2 emissions under different tillage-sowing practices in a rainfed crop rotation," *International Journal of Environmental Science and Technology*, 17, pp. 4563–4576. Available at: https://doi.org/10.1007/s13762-020-02804-y.

Hanhur, V. *et al.* (2020) "The effect of soil tillage on symbiotic activity of soybean crops," *Bulgarian Journal of Agricultural Science*, 26, pp. 365–374. Available at: https://www.agrojournal.org/26/02-13.pdf (Accessed: December 10, 2023).

Hosseini, S.Z. *et al.* (2016) "Effect of tillage system on yield and weed populations of soybean (*Glycine max* L.)". *Anais da Academia Brasileira de Ciencias*, 88(1), pp. 377–384. Available at: https://doi.org/10.1590/0001-3765201620140590.

James, A.T. and Yang, A. (2016) "Interactions of protein content and globulin subunit composition of soybean proteins in relation to tofu gel properties," *Food of Chemistry*, 194, pp. 284–289. Available at: https://doi.org/10.1016/j.foodchem.2015.08.021.

Karunakaran, V. and Behera, U.K. (2016) "Tillage and residue management for improving productivity and resource use efficiency in soybean (*Glycine max*) – wheat (*Triticum aestivum*) cropping system," *Experimental Agriculture*, 1(4), pp. 1–18. Available at: https://doi.org/10.1017/S0014479715000289.

Kjeldahl, J.A. (1883) "New method for the determination of nitrogen in organic matter," *Zeitschrift für Analytische Chemie*, 22, pp. 366–382. Available at: https://doi.org/10.1007/BF01338151.

Knapen, A. *et al.* (2007) "Resistance of soils to concentrated flow erosion: A review," *Earth-Science Reviews*, 80, pp. 75–109. Available at: https://doi.org/10.1016/j.earscirev.2006.08.001.

Kombiok, J.M. and Buah, S.S.J. (2013) "Tillage depth effects on nodulation, nitrogen fixation and yield of three soybean varieties in the Northern Savanna zone of Ghana," *African Journal of Agricultural Research*, 8, pp. 2340–2345. Available at: https://doi.org/10.5897/AJAR12.1304.

Kotecki, A. and Lewandowska, S. (2020) "Studia nad uprawą soi zwyczajnej (*Glycine max* (L.) Merrill) w południowo-zachodniej Polsce [Studies on the cultivation of soybean (*Glycine max* (L.) Merrill) in south-western Poland]," *Monografie*, 228. Wrocław. Poland: Wyd. UP Wrocław.

Księżak, J. and Bojarszczuk, J. (2022) "The seed yield of soybean cultivars and their quantity depending on sowing term," *Agronomy*, 12(5), 1066. Available at: https://doi.org/10.3390/agronomy12051066.

Lança Rodrígues, J.G.L. *et al.* (2009) "Effects of different soil tillage systems and coverages on soybean crop in the Botucatu Region in Brazil," *Spanish Journal of Agricultural Research*, 7(1), pp. 173–180. Available at: https://doi.org/10.5424/sjar/2009071-409.

Lopes, R.A.P. *et al.* (2007) "Efeito de diferentes coberturas vegetais e sistemas de preparo do solo na produção da cultura da soja [Effect of different vegetation covers and soil preparation systems on soybean crop production]," *Acta Scientiarum. Agronomy*, 29, pp. 507–515. Available at: https://www.redalyc.org/articulo.oa?id=303026575011 (Accessed: December 10, 2023).

Luboiński, A. and Markowicz, M. (2017) "Wpływ systemu nawożenia azotem na plonowanie trzech odmian soi (*Glycine max* (L.) Merr.) [Effect of nitrogen fertilization system on yielding of three non-GMO soybean varieties]," *Fragmenta Agronomica*, 34, pp. 66–75. Available at: https://pta.up.poznan.pl/pdf/2017/FA%2034(3)%202017%20Luboinski.pdf (Accessed: December 10, 2023).

Małecka, I., Blecharczyk, A. and Dobrzeniecki, T. (2007) "Zmiany fizycznych i chemicznych właściwości gleby w wyniku stosowania uproszczeń w uprawie roli [Changes in soil physical and chemical properties caused by reduced tillage]," *Fragmenta Agronomica*, 24(1), pp. 182–189. Available at: https://pta.up.poznan.pl/pdf/Fragm.%20Agron.%20vol.%2024%20(2007)/24(1)%202007.pdf (Accessed: December 10, 2023).

Małecka, I. *et al.* (2012) "The effect of various long-term tillage systems on soil properties and spring barley yield," *Turkish Journal of Agriculture and Forestry*, 36, pp. 217–226. Available at: https://doi.org/10.3906/tar-1104-20.

Matsuo, N. *et al.* (2019) "Design and evaluation of a one-operation shallow up-cut tillage sowing method for soybean production," *Plant Production Science*, 22(4), pp. 465–478. Available at: https://doi.org/10.1080/1343943X.2019.1625274.

Meese, B. *et al.* (1991) "Corn/soybean rotation effect as influenced by tillage, nitrogen, and hybrid/cultivar," *Journal of Production Agriculture*, 4, pp. 74–80.

Monsefi, A. *et al.* (2014) "Effect of tillage and residue management on productivity of soybean and physic–chemical properties of soil in soybean – wheat cropping system," *International Journal of Plant Production*," 8(3), pp. 429–439. Available at: https://doi.org/10.22069/ijpp.2014.1618.

Morris, N.L. *et al.* (2010) "The adoption of noninversion tillage systems in the United Kingdom and the agronomic impact on soil. crops and the environment – A review," *Soil Tillage Research*, 108(1–2), pp. 1–15. Available at: https://doi.org/10.1016/j.still.2010.03.004.

Morrison, J.E. Jr. (2002) "Strip tillage for "no-till" row crop production," *Applied Engineering in Agriculture*, 18(3), pp. 277–284. Available at: https://doi.org/10.13031/2013.8593.

Morrison, J.E. Jr. and Sanabria, J. (2002) "One-pass and two-pass spring strip tillage for conservation row-cropping in adhesive clay soils," *Transaction of the American Society of Agricultural and Biological Engineers*, 45, pp. 1263–1270.

Nogala-Kałucka, M. (ed.) (2016) „Analiza żywności. Wybrane metody oznaczeń jakościowych i ilościowych składników żywności" [Food analysis. Selected methods of qualitative and quantitative determination of food ingredients]". Poznań, Poland: Wyd. UP Poznań.

Page, K.L. *et al.* (2020) "The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield," *Frontiers in Sustainable Food Systems*, 4, 31. Available at: https://doi.org/10.3389/fsufs.2020.00031.

Pedersen, P. and Lauer, J.G. (2003) "Corn and soybean response to rotation sequence. Row spacing, and tillage system," *Agronomy Journal*, 95, pp. 965–971. Available at: https://doi.org/10.2134/agronj2003.9650.

Pittelkow, C.M. *et al.* (2015) "When does no-till yield more? A global meta-analysis," *Field Crops Research*, 183, pp. 156–168. Available at: https://doi.org/10.1016/j.fcr.2015.07.020.

Potratz, D.J. *et al.* (2020) "Strip-till, other management strategies, and their interactive effects on corn grain and soybean seed yield," *Agronomy Journal*, 112, pp. 72–80. Available at: https://doi.org/10.1002/agj2.20067.

Radomski. C. (1973) *Agrometeorologia [Agrometeorology]*. Warszawa: PWN.

Redondo-Cuenca, A., Villanueva-Suárez, M.J. and Mateos-Aparicio, I. (2008) "Soybean seeds and its by-product okara as sources of dietary fibre. Measurement by AOAC and Englyst methods," *Food Chemistry*, 108(3), pp. 1099–1105. Available at: https://doi.org/10.1016/j.foodchem.2007.11.061.

Santín-Montanyá, M.I. *et al.* (2014) "Dry pea (*Pisum sativum* L.) yielding and weed infestation response, under different tillage conditions," *Crop Protection*, 65, pp. 122–128. Available at: https://doi.org/10.1016/j.cropro.2014.07.017.

Skowera, B. (2014) "Zmiany warunków hydrotermicznych na obszarze Polski (1971–2010) [Changes of hydrothermal conditions in the Polish area (1971–2010)]," *Fragmenta Agronomica*, 31(2), pp. 74–87. Available at: https://pta.up.poznan.pl/pdf/2014/FA%2031(2)%202014%20Skowera.pdf (Accessed: December 10, 2023).

Soane, B.D. *et al.* (2012) "No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment," *Soil Tillage Research*, 118, pp. 66–87. Available at: https://doi.org/10.1016/j.still.2011.10.015.

Soxhlet, F. (1879) "The weight analytic determination of milk fat," *Polytechnisches Journal*, 232, pp. 461–465.

Stipešević, B. *et al.* (2009) "Influence of different soil tillage systems on soybean yield and yield components," *Tarım Makinaları Bilimi Dergisi*, 5(3), pp. 263–267. Available at: https://dergipark.org.tr/tr/download/article-file/119016 (Accessed: December 10, 2023).

Szwejkowska, B. (2005) "Wpływ intensywności uprawy grochu siewnego na zawartość i plon białka [Effect of cultivation intensity on protein content and yields in field pea]," *Acta Scientiarum Polonorum, Agricultura*, 4(1), pp. 153–161.

Townsend, T.J., Ramsden, S.J. and Wilson, P. (2016) "How do we cultivate in England? Tillage practices in crop production systems," *Soil Use and Management*, 32(1), pp. 106–117. Available at: https://doi.org/10.1111/sum.12241.

Vita de, P. *et al.* (2007) "No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy," *Soil and Tillage Research*, 92(1–2), pp. 69–78. Available at: https://doi.org/10.1016/j.still.2006.01.012.

Vyn, T.J., Opoku, G. and Swanton, C.J. (1998) "Residue management and minimum tillage systems for soybean following wheat," *Agronomy Journal*, 90(2), pp. 131–138. Available at: https://doi.org/10.2134/agronj1998.00021962009000020002x.