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The Effect of Sustainable Tillage Systems on Faba Bean Yield in a Long-Term Experiment in Poland

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Abstract: In recent times, there has been a trend towards sustainable agriculture in the world, which is aimed at protecting the production potential of the soil and ensuring stable agricultural production. Conservation agriculture is one way to ensure sustainable production. The main principles of conservation agriculture are crop diversification, minimizing tillage, and maintaining soil cover with plant residues. An important role in crop diversification is assigned to legumes. The research was conducted in 2016–2019 based on a long-term experiment established in 1999 (Brody/Poznań). The experiment with faba bean included four variants of tillage: 1—conventional tillage (CT), 2—reduced tillage (RT), 3—strip-tillage (ST), and 4—no-tillage (NT). The research took place in two extremely different weather conditions. Two very favorable years and two with catastrophic drought. Weather conditions had a greater effect on faba bean yields than the tillage systems. The highest faba bean seed yield was obtained in 2017. The seed yield ranged from 6.73 t ha^{-1} in NT to 7.64 t ha^{-1} after ST. A high seed yield (4.94–5.97 t ha^{-1}) was also in 2016. In years characterized by low rainfall (2018 and 2019), the average seed yield was 1.89 and 1.74 t ha^{-1}, respectively. Considering the sustainability of the assessed tillage systems in faba bean, both in terms of environment and production, RT and ST should be indicated as the most sustainable. They limit the intensity of tillage and can be classified as conservation tillage, as opposed to conventional tillage. NT provides the best soil protection and conservation, but in favorable weather conditions, it limits the yield level of faba beans. The yields obtained in RT and ST technologies were high, both in favorable and extremely unfavorable years. Given the increasing climatic instability and unpredictable weather, yield stability in various conditions is as important as ensuring conservation tillage.

Keywords: conservation tillage; sustainable crop production; crop quality; *Vicia faba* L.; crop residues

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1. Introduction

The soil of an arable field is the basic means of agricultural production, and its condition determines not only the efficiency of production but also the sustainability of the system. The commonly used intensive methods of plant cultivation lead to soil degradation. The strong link between soil health and soil safety creates the need for sustainable agriculture activities, which are aimed at protecting the productive potential of the soil [1–5]. The main principles of sustainable agriculture are crop diversification, which can minimize the excessive share of cereals in the sowing structure, and the use of integrated agricultural production methods, in which legumes play an essential role [6–10]. The argument for this group of plants is that they can be used for seed, green matter, and ploughing, as a so-called green manure. Due to the chemical composition of the seeds, they serve as a significant component of high-protein feed [11–14] and the human diet [11,14,15]. The fodder value of the seeds of this group of plants is primarily determined by their high-protein and essential amino acid content, their high nutrient digestibility, and the fact that they can be used in the diet of all livestock species [13–15]. However, they contain anti-nutritional substances such as alkaloids, glycosides, oligosaccharides, trypsin inhibitors, tannins, and others, which are factors that limit their use in animal nutrition [15,16]. Among the high-protein legumes, the faba bean (*Vicia faba* L.) deserves special attention because of its highest yield potential and the rich chemical composition of its seeds, which determine its nutritional value [11,14]. The seeds are characterized by their high protein content and digestibility, as well as minerals, vitamins, and many bioactive substances [13].

Besides its fodder importance, faba beans, like other legumes, have a beneficial effect on the soil environment, their physicochemical and biological properties; among other things, it has a phytomelioration function thanks to their strongly developed root system. Furthermore, the cultivation of faba bean during crop rotation reduces the incidence of soil nematodes [17]. A significant advantage of legumes is their ability to fix atmospheric nitrogen, which is of great importance both economically and ecologically [16–23]. The most energy-efficient and effective form of nitrogen fertilization, allowing a significant reduction in the amount of this element brought into the soil in the form of mineral fertilizers, is the introduction of legumes into the crop rotation [24]. According to a study conducted by Ntatsi et al. [25], the total amount of nitrogen that is biologically reduced by faba bean ranges from 119 to 194 kg ha^{-1}, depending on the cultivation technology and variety. It is noteworthy that faba bean seeds can also be utilized in medicine to produce pharmaceuticals. Faba bean plants accumulate in large quantities in their various organs the substance L-Dopa (amino acid), which is a precursor of dopamine, used worldwide to alleviate the effects of Parkinson’s disease. Natural L-Dopa has the potential to mitigate the adverse effects of dopamine that has been chemically synthesized [14,26,27].

Despite the numerous advantages of legumes, their cultivation prevalence remains low. It is estimated that in the European Union, they occupy only about 2% of arable land [9]. In 2017, the total area of legume crops in Poland was 272 thousand ha, of which 77% were fodder varieties [28].

The low interest of farmers in legumes, especially faba beans, is due to their low profitability and low yield stability. Faba beans are a plant that is highly susceptible to abiotic stresses, primarily due to the course of weather conditions. The primary causes of low bean yields are the absence of rainfall and elevated temperatures, particularly during flowering and pod development.

The primary reasons for the low interest in faba bean cultivation are the high variability of yields from year to year and the high cost of cultivation. Therefore, it is imperative to seek genotypes that are more resilient to drought stress [29,30] and for solutions to reduce the cost of cultivating this species [2,31]. According to a study by Czerwińska–Kayzer and Florek [32], the largest share of production costs in legume cultivation is accounted for by agrotechnical treatments (50%), followed by seed purchase (16%). Therefore, it is expedient to seek to reduce costs and therefore improve the profitability of growing this group of crops. One approach may be to transition from the costly and energy-intensive plough tillage [1,2,31,33] approach to alternative solutions that involve the implementation of reduced (non-inversion) systems, including the complete abandonment of mechanical action on the soil and the utilization of direct seeding. The benefits of using reduced tillage systems are significant, as they not only reduce energy and labor inputs by around 35% but also have a positive impact on the soil environment. They improve soil organic carbon and water content, soil structure, reduce topsoil crusting, reduce erosion problems, and improve soil biological properties [33–37].

In the last 20–30 years, it has been possible to observe an increase in interest in agricultural practice in the technologies included in conservation tillage. This system is based on leaving at least 30% of the field surface covered with mulch. Zero tillage (no-tillage) works best with this system. However, in Europe, compared to South and North America, the share of no-tillage cultivation is low and amounts to only 5.2% [5]. In addition to direct sowing, other technologies that do not use a moldboard plough can also be used to establish conservation tillage.

This issue has been extensively researched, mainly in cereal crops, while there is less work on the effect of conservation tillage on the yield of legumes, especially faba bean [23,38–41]. Moreover, there are no scientific studies regarding the response of faba bean to strip-tillage (strip-till). Among the crop species that exhibit favorable tolerance to reduced tillage, legumes are mentioned, despite research findings indicating varying production effects for this group of crops [31,42–44]. Some authors suggest that this may be due to the different duration of the experiment [3,45,46], the course of weather conditions [3,45,47], or the increase in bulk density and soil compactness, especially during the first years of study [21,23,48,49]. This can inhibit and reduce field emergence and plant root system development, and result in slower plant aboveground biomass growth and nutrient accumulation compared to conventional tillage [47].

In addition to the protection of the soil environment, achieving stable plant yields is also important for the sustainability of the system. The increased risk of yield reduction is also one of the biggest problems in implementing sustainable agriculture practices into practice.

The aim of this study was to evaluate the sustainability of various long-term conservation tillage practices for faba beans in Polish conditions.

2. Materials and Methods

The research was conducted using a long-term experiment established in 1999 at the Experimental Station Brody (52°43′ N, 16°30′ E), which belongs to the Poznań University of Life Sciences. They were located on typical podzolic soil, with boulder clay and light and strong loamy sand. The soil was classified as Albic Luvisols (2% clay, 16% silt, 82% sand) and, based on grain size, as loamy sand underlined by loam. The topsoil before the experiment contained 1.4% organic matter. The levels of available P, K, and Mg were, respectively, 207, 119, and 32 mg kg^{-1}. The pH of the solution was 6.5 (measured in 1 M KCl), and the bulk density was 1.41 Mg m^{-3}. Before the establishment, winter wheat was grown, under which ploughing was applied. The single-factorial experiment was conducted using the randomized block method in four replications, with the duration spanning from 2016 to 2019.

Faba bean Albus variety was grown in a four-course rotation (75% cereals) as follows: faba bean (since 2016, and peas before that), winter wheat, spring barley, winter triticale. The size of the plots at the establishment of the experiment was 36 m^{-2} (4 m wide and 9 m long). The straw of all crops grown was removed from the field.

The experimental scheme included the following four tillage systems:

1. Conventional tillage (CT),
2. Reduced tillage (RT),
3. Strip-tillage (ST),
4. No-tillage with direct drilling into stubble (NT).

In CT, after harvesting the previous crop, the soil was ploughed with a disc harrow (2.5 m wide, Euro-Masz, Jabłonna, Poland) to a depth of 8 cm. In late autumn, the soil was ploughed with a 3-blade moldboard plough to a depth of 25 cm, and in spring, one week before sowing faba bean, the soil was treated with a cultivating unit (drag, cultivator, two rolling baskets) to the depth of faba bean sowing (8 cm). At RT, cultivation was done with a stubble cultivator (2.5 m wide, UNIA GROUP, Grudziądz, Poland) at a depth of 10 cm. At NT, only sowing was done directly into the stubble after the previous crop. In CT, RT, and NT, seed sowing was executed using a seeder manufactured by the American company Great Plains Manufacturing (Salina, Kansas, USA), which was equipped with a coulter for cutting crop residues, a double disc opener, and a single press wheel, with a spacing of 18 cm. In the ST, cultivation and sowing were carried out with a prototype, field-based strip-till unit, consisting of seven working sections mounted on a main frame, suspended from the rear implement linkage of an agricultural tractor. The fundamental structure of the section consisted of a narrow straight tine, followed by a pair of discs and a tire roller. Behind the unit, a seed drill (UNIA GROUP, Grudziądz, Poland) with disc coulters (2 m wide) was hitched behind the cultivator. Within the ST, a 12 cm wide strip was cultivated, and the 24 cm wide inter-row was left uncultivated. In the cultivated strip, two rows of seeds were sown, each 5 cm from the center of the cultivated strip. The strip tillage was carried out to a depth of 25 cm, together with sowing in spring, in one working pass of the unit. All cultivation variants were carried out using a ZETOR Forterra 10641 tractor (Zetor Tractors, Brno, Czech Republic).

CT with a moldboard plough is a typical system used in Europe. It is also a typical example of unbalanced management and a lack of litter on the surface. In the experiment, it is a control object to which other, potentially conservative systems are compared. NT is the most conservative tillage system, but it carries the greatest risk of yield reduction. RT, which involves shallow mixing of the soil to a small depth, is the most widely used in Poland among all non-inversion technologies. ST is a new technology that is still rare in Poland, especially in narrow-row crops, but is very promising. It allows for deep soil loosening, and at the same time, the soil between rows remains practically intact.

In autumn, mineral fertilization was applied at P_2O_5—60 kg and K_2O—90 kg, and in spring, 40 kg N ha^{-1}. Faba bean was sown in all years of the study at a density of 60 seeds/m^{-2} at the end of March or the beginning of April. After sowing faba bean, weeds were controlled with dimethenamid-P + pendimethalin (Wing P 462.5 EC at 4.0 l ha^{-1}, post-emergence with bentazone + imazamox (Corum 502.4 SL at 1.25 l ha^{-1}, with adjuvant (Dash HC at 1.0 l ha^{-1}). At RT, ST, and NT, glyphosate (Roundup 360 SL, 4 l ha^{-1}) with adjuvant (AS 500 SL at 1.5 l ha^{-1}) was additionally applied after harvesting the previous crop to control perennial weeds and cereal smuts.

During flowering and pod development, beta-cyfluthrin, acetamiprid (Mospilan 20 SP, 0.2 kg ha^{-1}), (Bulldock 025 EC, 0.25 l ha^{-1}), and thiachloprid + deltamethrin (Proteus 110 OD, 0.75 l ha^{-1}) were applied to control pests. One week before the faba bean harvest, diquat (Dessicash 20 SL, 3.0 l ha^{-1}) was applied. To manage the disease, chlorothalonil (Gwarant 500 SC, 2.0 l ha^{-1}) and azoxystrobin (Amistar 250 EC, 1.0 l ha^{-1}) were applied in 2016 and 2017. Harvesting was carried out using a Wintersteiger field combine with automatic weighing in the third decade of August in 2016 and 2017, and in the first decade of August in 2018 and 2019. The seed yield from a 27 m^{-2} plot was converted to a moisture content of 15%. Additionally, yield components such as the number of plants per unit area, the number of pods per plant, the number of seeds per pod, and the weight of 1000 seeds were assessed. Plant density was determined before harvest in four randomly selected rows along a 1-m running section of each plot and converted to 1 m^{-2}. The number of pods per plant was estimated by randomly sampling 25 plants from each plot, and the number of seeds per pod was based on 50 randomly selected pods. The weight of 1000 seeds was obtained by counting on an electronic counter and weighing twice 500 seeds each from a sample from the combine harvest. Straw and root yields were included in the weight of crop residues. To determine these, plant and root samples were taken before harvest from each plot from two adjacent rows over a distance of one meter long (0.36 m^{-2}), After separation of the seeds, the straw was weighed separately together with the pods and the roots were counted in dry matter per 1 ha^{-1}.

The nitrogen content of seeds, straw, and roots was determined by mineralizing samples in sulphuric acid on a Foss TM apparatus and by distillation on a Kjeltec 2200 (Foss, Hillerød, Denmark) flow analyzer. The detection was carried out using a titration solution. Seed protein content was calculated from the product of seed nitrogen content and a constant of 6.25. Based on seed protein percentage and actual yield, protein production per ha was calculated.

The fertilizer value of the crop residues was presented as the quantity of nitrogen remaining in the residues per hectare, which was determined based on the dry matter yield of straw and roots and their nitrogen content.

Root nodules were assessed during the flowering period of broad bean on the basis of 25 plants from each individual plot. Physical and chemical properties of the soil were determined based on the methodologies presented in the study by Małecka et al. [49]. The results were subjected to an analysis of variance with a significance level of 0.05 using the program FR-ANALWAR 5.2 (Rudnicki, Bydgoszcz, Poland). The significance of the variation in the results was assessed using the Fisher–Snedecor test, with a significance level of $p = 0.05$. The significance of differences between means was estimated using the Tukey test.

The weather conditions during the study years (2016–2019) were developed based on data recorded by an automatic meteorological station located at the Experimental Station in Brody. The climate of Wielkopolska, where the Brody Experimental Station is located, is characterized by high variability and diversity of weather types. The region is under the influence of polar-maritime and polar-continental air masses. The weather conditions during the faba bean growing season in the research years varied (Tables 1 and 2).

Table 1. Average air temperature (°C) during the faba bean growing season at the Experimental Station Brody, 2016–2019, compared to long-term temperatures.

Year/Month	March	April	May	Jun	July	August	March–August
2016	4.0	8.8	15.3	18.2	19.1	17.9	13.9
2017	6.7	7.7	14.0	17.7	18.4	18.4	13.8
2018	0.7	12.9	17.1	19.1	20.7	21.4	15.3
2019	6.5	10.4	12.2	22.4	19.3	20.7	15.3
Average (1961–2015)	3.0	8.1	13.3	16.6	18.3	17.6	12.8

Table 2. Total precipitation (mm) during the faba bean growing season at the Experimental Station Brody, 2016–2019, compared to long-term precipitation.

Year/Month	March	April	May	June	July	August	March–August
2016	31.2	29.7	76.1	94.8	114.5	57.9	404.2
2017	40.5	25.7	49.2	106.0	160.8	150.6	532.8
2018	20.6	65.3	19.2	31.5	134.9	20.0	291.5
2019	48.2	11.9	77.8	8.4	63.3	28.2	237.8
Average (1961–2015)	39.4	36.9	57.3	64.7	81.5	66.8	346.6

In 2016, the entire growing season was warmer than in previous years, with slightly lower rainfall at the beginning and end of the growing season (March, April, August). During the remaining months, when water demand is particularly high, the rainfall was 20–30 mm above the multi-year average. The 2017 growing season was characterized by a warmer March, a cooler April, and a slightly higher average temperature from May to August in comparison to the previous multi-year period. The precipitation only in April and May was slightly below the multi-year average, while the remaining months, especially June, July, and August, were well above the multi-year average.

The seasons of 2018 and 2019 can be regarded as the warmest during the study period, except March 2018, where the average temperature was 2.3 °C lower than the recorded temperature, resulting in the coldest month. The study years with the highest average air temperatures had an unfavorable distribution of precipitation, as precipitation deficits in 2018 occurred in the months of March, May, June, and August. Additionally, the high precipitation in July was of a thunderstorm nature and concerned almost entirely the second decade of that month. Furthermore, during the last year of the study, unfavorable moisture conditions prevailed, especially during the flowering and pod setting period of the faba bean. To summarize, it can be stated that during the research period, there were two years with favorable weather conditions (2016 and 2017) and two years with extremely unfavorable conditions (2018 and 2019) for high faba bean yields.

Statistically significant differences between the groups in the field experiment were determined by a two-way ANOVA. The Shapiro–Wilk test was employed to verify if the distribution of results in the analyzed data aligned with the norm, while Levene's test was employed to evaluate the assumption that the variance was homogeneous. Corrections for unequal variances were introduced if the results indicated that the assumption of homogeneity of variance was not fulfilled; Welch's test was applied. When the results of the ANOVA test were statistically significant, it was assumed that at least one of the groups differed from the others. We performed a Tukey HSD post-hoc test to determine which group averages were statistically significantly different from one another. The homogeneous groups within the average of the factors are indicated by uppercase letters, and the interaction between the factors is indicated by lowercase letters.

The interaction of the level of one factor with the level of another factor on a given variable is presented graphically using the Statistics software Statistica v.13.1 (StatSoft Polska Sp. z o.o., Kraków, Poland) (Figure 1). To determine the relationship between the variables and the extent to which they were related, Pearson correlation coefficients were used. A seven-point scale was used to measure and interpret the significance of a significant correlation, where 0.0 to 0.19—very weak correlation, 0.20 to 0.39—weak correlation, 0.4 to 0.59—moderate correlation, 0.60 to 0.79—strong association, 0.80 to 0.99—very strong association, 1.0—perfect association [50].

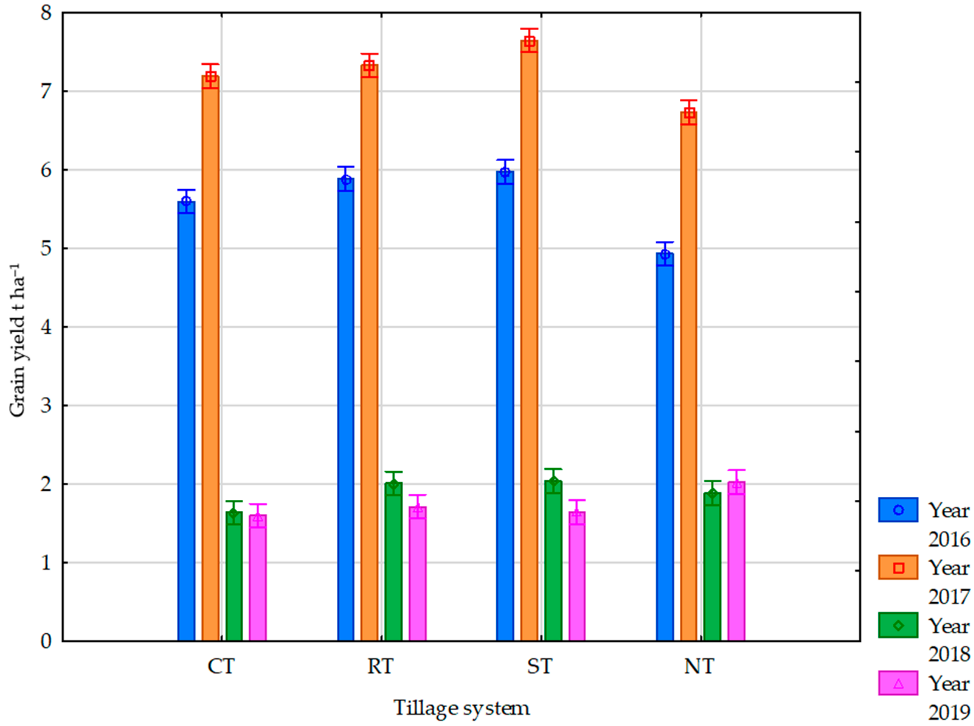

Figure 1. Effect of tillage systems and years on faba bean seed yield. CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage.

3. Results and Discussion

3.1. Faba Bean Seed Yield and Yield Components

The results of the research conducted in Western Poland indicate a significant dependence of the effect of tillage systems on faba bean yield on the years of the experiment, especially on the course of weather conditions (precipitation and its distribution, temperature, water stress). In 2017, the highest faba bean seed yield was obtained, in all tillage variants, when the total precipitation for the growing season was 184 mm higher than in the long-term period (Table 3). On average, for the tillage system, the seed yield was 7.22 t ha^{-1} and varied from 6.73 t ha^{-1} in NT to 7.64 t ha^{-1} after ST application. In the initial year of the experiment (2016), the faba bean seed yield ranged from 4.93 to 5.97 t ha^{-1}, and the total rainfall was 55.4 mm higher than in the long-term period.

Table 3. Effects of different tillage systems on faba bean seed yield (t ha^{-1}).

Treatment (Factor T)	Year of Study (Factor Y)				Average (T)
	2016	2017	2018	2019	
CT	5.76 de	7.19 b	1.63 j–m	1.60 j–n	4.04 C
RT	5.88 de	7.33 b	2.00 ghi	1.71 ijk	4.23 B
ST	5.97 d	7.64 a	2.03 g	1.64 jkl	4.32 A
NT	4.93 f	6.73 c	1.88 g–j	2.02 gh	3.89 D
Average (Y)	5.63 B	7.22 A	1.89 C	1.74 C	-

CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; values marked with the same capital letters (Y and T separately) and lower case letters (Y and T interaction) are not significantly different at $p = 0.05$.

The analysis of variance demonstrated a significant effect of the tillage system on faba bean yield in all years of the study. In 2016 and 2017, which were the years with the highest rainfall during the faba bean growing season, a negative effect of NT on faba bean yield was noted. The seed yield in the years analyzed was lower than the average yield in other tillage variants, by 16.0 and 8.8%, respectively. Furthermore, it is possible to note the trend of the most favorable effect of ST on seed yield. In years with low precipitation and high air temperature during the bean growing season, which further aggravated the severe soil drought (2018 and 2019), the average seed yield for the tillage system was 1.89 and 1.74 t ha^{-1}, respectively. This was 3–4 times lower than in years with favorable moisture conditions. In the dry years (2018 and 2019), in contrast to the wet years, higher bean seed yields were recorded in NT compared to the yield obtained in CT, by 15.3 and 26.3%, respectively. These relationships may be due to the higher soil moisture in NT, which may favor the development of the faba bean root system [21,51,52]. Different results were found when evaluating the influence of tillage systems on faba bean yield. The studies by Romaneckas et al. [23] and Alhajj et al. [38] indicate that there is no effect of the tillage system on faba bean yield. However, Badagliacca et al. [48] found a 23% higher seed yield of faba bean in NT compared to CT.

The results confirm the significant dependence of faba bean yield on weather conditions, such as the highly significant impact of rainfall and temperature during the faba bean growing season on the number of plants per m^2, seed and straw yield, and 1000 seed weight of faba bean [38]. Furthermore, Romaneckas et al. [23], Toker [53], and Alarcón et al. [54] found that weather conditions had a greater effect on faba bean yields than the tillage systems. However, Ruisi et al. [22] found that faba bean yields vary more than those of other crops because this crop is more sensitive to environmental and biological factors.

Table 4 contains the results of an analysis of variance for the effect of tillage systems on yield components. The results indicate a highly significant interaction between the research factor and the year of the experiment. In 2018 and 2019, adverse moisture conditions contributed to the deterioration of yield elements, including plant density per unit area, before harvest. In 2016 and 2017, considered favorable in terms of weather conditions, the average stocking rate was comparable to the average number of plants recorded in dry years (2018 and 2019). These results may be due to similar moisture conditions during the sowing and emergence period of the faba bean during the study years. Furthermore, the average daily temperature was higher in 2017 and 2019 than in 2016 and 2018, which may have contributed to the faster and higher field emergence of faba bean. According to Etemadi et al. [14], most legumes show high sensitivity to low soil temperature during the germination period. In years with favorable moisture conditions, the quantity of pods per plant, number of seeds per pod, and weight of 1000 seeds were higher than in dry years, as confirmed by Giambalvo et al. [21]. The competition for assimilates can lead to significant levels of flower and pod shedding in the canopy of numerous legume species, and when this occurs at the onset of their development, it can significantly impact the final yield [55].

The results of the statistical analysis indicated that tillage systems had a highly significant ($p < 0.01$) effect on the number of plants per unit area, the number of pods per plant (only in 2018), and the weight of 1000 seeds in both 2018 and 2019. However, the effect on the number of seeds per pod in 2018 was less significant ($p < 0.05$). Plant density was the primary determinant of the variations in faba bean seed yields between tillage systems, as shown by Figure 1 and Table 3, with the other yield components playing a minor role. The lowest preharvest bean planting density was noted in the NT in 2016 and 2017, the years with the lowest seed yield. The number of plants per unit area in CT decreased by 13.2% in 2016 and by 5.1% in 2017, respectively. However, in dry years, when yields were higher in NT, higher planting density was also observed on these sites than in CT. According to Lopez–Bellido et al. [55], the seed yield of faba beans depends on the preharvest plant density and, consequently, the number of pods per plant. Other yield factors, such as the quantity of seeds per pod and the weight of 1000 seeds, are largely influenced by genotype. Giambalvo et al. [21] found no difference in 1000-seed weight between CT, RT, and NT tillage systems. However, the results of individual legume yield components are not conclusive. Additionally, a reduction in one yield component often leads to an increase in other yield components, causing a so-called compensatory effect [44].

Table 4. Yield components of faba bean under different tillage systems.

Treatment (Factor T)	Year of Study (Factor Y)				Average (T)
	2016	2017	2018	2019	
	Density (plants m^{-2})				
CT	44.0 g–j	54.5 a–d	46.5 f–h	50.4 a–e	48.9 A
RT	42.8 h–j	55.2 ab	44.2 g–j	50.1 b–g	48.1 A
ST	42.7 h–j	56.4 a	41.3 h–j	45.4 f–i	46.5 A
NT	38.2 j	51.7 a–d	47.1 e–h	54.6 a–c	47.9 A
Average (Y)	41.9 C	54.5 A	44.8 C	50.1 B	-
	Pods $plant^{-1}$ (no.)				
CT	6.5 e–g	7.5 bc	3.1 jk	3.0 k	5.0 BC
RT	6.6 ef	7.7 ab	3.6 ij	3.1 jk	5.2 AB
ST	6.8 de	8.2 a	3.9 i	3.2 jk	5.5 A
NT	6.1 f–h	7.1 cd	3.2 jk	3.3 i–k	4.9 BC
Average (Y)	6.5 B	7.6 A	3.5 C	3.1 D	-
	Seeds pod^{-1} (no.)				
CT	3.6 a	3.4 a	2.9 a	2.6 a	3.1 C
RT	3.7 a	3.5 a	3.2 a	2.6 a	3.2 B
ST	3.6 a	3.4 a	3.1 a	2.7 a	3.2 B
NT	3.8 a	3.6 a	3.1 a	2.7 a	3.3 A
Average (Y)	3.7 A	3.5 B	3.0 C	2.7 D	-
	Thousand seed weight (g)				
CT	562.1 b–d	508.7 e	395.7 o	406.2 l–n	468.2 D
RT	572.0 a	504.9 e–h	405.1 l–n	418.9 i–k	475.2 A–C
ST	569.3 ab	505.1 e–g	407.4 lm	422.0 ij	475.9 AB
NT	562.4 bc	507.1 ef	409.3 l	426.5 i	476.3 A
Average (Y)	566.5 A	506.4 B	404.4 D	418.4 C	-

CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; values marked with the same capital letters (Y and T separately) and lower case letters (Y and T interaction) are not significantly different at $p = 0.05$.

3.2. Protein Content and Production in Faba Bean Seeds

Given the nutritional value of legume seeds, especially the content of protein, carbohydrates, B vitamins, and minerals, which depends not only on the species but also on the environmental conditions [11], faba beans are among the most important species among legumes in the world. The impact of study factors and years on seed protein content is directly related to the quantity of nitrogen absorbed and accumulated in the seeds. On average, for the years of the 2016–2019 research, the protein content of faba bean seeds did not differ significantly depending on the tillage system and ranged from 29.6 to 30.3% (Figure 2). Due to the slight variation in protein concentration in faba bean seeds, protein production was mainly determined by the seed yield. The data indicate that tillage systems have a significant effect on protein production in faba bean seeds, although this effect varies from year to year. The highest level of protein production was recorded in 2017 in ST (1936 kg ha^{-1}), which coincided with the most favorable weather conditions during the faba bean growing season (Table 5). After applying CT, RT, and NT, protein production was significantly reduced by 6.6, 4.5, 6.6, and 11.1%, respectively. In the first year of the study (2016), high protein production was recorded in the range of 1328 to 1588 kg ha^{-1}, with weather conditions classified as good. As in 2017, the highest protein production was found in ST. A reduction in this parameter occurred after the application of the other crop variants, by 7.2% (CT), 5.9% (RT), and 16.4% (NT). Moreover, there was no significant difference in protein yield between RT and CT. In dry years (2018 and 2019), protein production decreased by 3–4 times compared to years with favorable weather conditions. There were no significant differences in protein production scores among RT, ST, and NT in 2018 and between CT, RT, and ST in 2019. In 2018, a significantly lower protein yield was achieved in CT, which was 18.4% lower compared to the average yield for the other crop variants. Additionally, it is noteworthy that in the driest year (2019), indeed, the highest protein production was found in NT; it was 21.1% higher in relation to the average yield in CT, RT, and ST. Previous studies have indicated a higher nitrogen uptake in legume seeds in the NT and the RT compared to the CT [56]. In no-till systems, conditions are created that are more conducive to the more abundant colonization of faba bean roots by specific bacteria of the Rhizobium genus. This leads to a more active fixation of atmospheric nitrogen in the process of biological reduction [18,22,41,57].

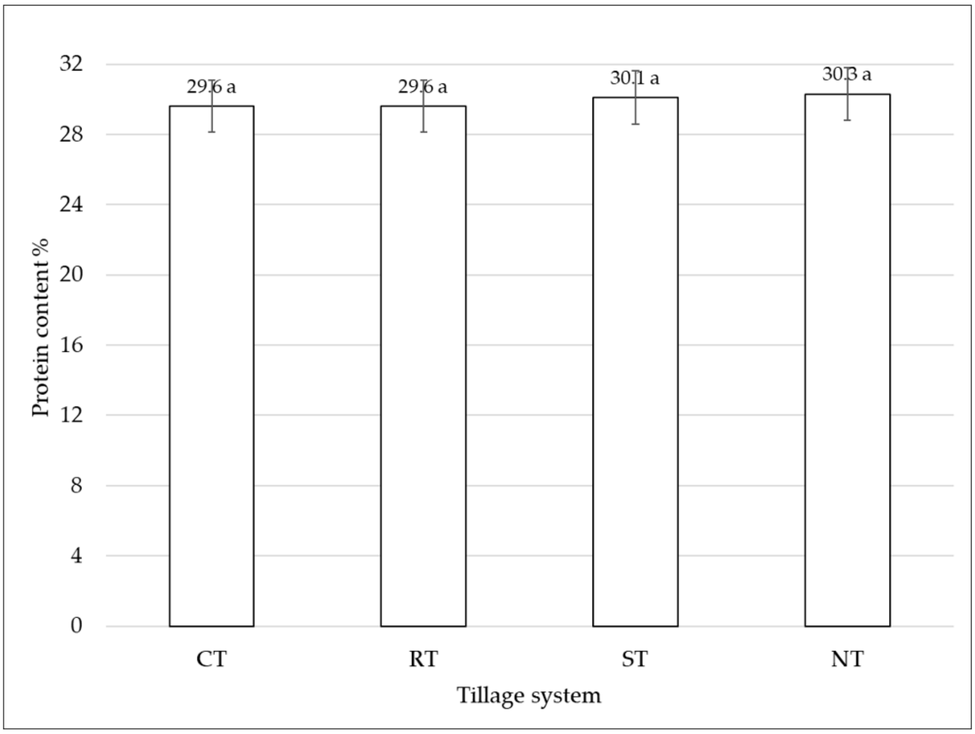

Figure 2. Effect of different tillage systems on faba bean seeds protein content (average from 2016 to 2019). CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; values marked with the same letters are not significantly different at $p = 0.05$.

Table 5. Effect of different tillage systems on faba bean seeds protein production.

Treatment (Factor T)	Year of Study (Factor Y)				Average (T)
	2016	2017	2018	2019	
CT	1473 fg	1809 bc	418 jkl	389 l	1022 C
RT	1494 f	1849 b	511 i	417 kl	1068 B
ST	1588 e	1936 a	531 i	400 l	1114 A
NT	1328 h	1721 d	495 ij	487 i–k	1008 C
Average (Y)	1471 B	1829 A	489 C	423 D	-

CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; values marked with the same capital letters (Y and T separately) and lower case letters (Y and T interaction) are not significantly different at $p = 0.05$.

3.3. Crop Residues

In no-till systems, conditions are created that are more conducive to the more abundant colonization of faba bean roots by specific bacteria of the Rhizobium genus. This leads to a more active fixation of atmospheric nitrogen in the process of biological reduction [21,22,41,58]. Due to their symbiosis with bacteria, legumes have a beneficial effect on soil fertility. Nitrogen remains bound in post-harvest residues (roots, straw, and pods) and can be partially secreted into the soil if present in excess. The significance of legumes in soil fertilization is widely recognized yet often overlooked in the presentation of the effects of cultivating this group of plants [59,60]. Crop residues represent a valuable source of organic matter in the soil and are essential, particularly in sandy soils where they enhance the sorption complex. They play an important role in limiting evaporation and preserving moisture in the soil. They possess superior properties compared to cereal crop residues owing to their higher nitrogen content. Furthermore, straw contains less lignin and has a lower C/N ratio, which makes it more easily decomposable and more suitable for fertilizer purposes than cereal straw [61,62].

In our own research, the mass of faba bean post-harvest residues (roots + straw and pods) depended on the tillage system and the course of weather conditions during the faba bean growing season and their interaction (Table 6). In the wet years (2016 and 2017), the average weight of crop residues was between 7.38 and 7.95 t DM ha^{-1}, whereas in the dry years (2018 and 2019), it was between 2.81 and 3.02 t DM ha^{-1}. The weight of post-harvest residues in faba bean cultivation was less differentiated by tillage systems to a lesser extent. During the study years, a comparable weight of post-harvest residues was observed in conventional, reduced, and strip tillage, ranging from 5.28 to 5.64 t DM ha^{-1}. The direct sowing of faba bean resulted in a reduction of 12.5% in the weight of post-harvest residues (roots, straw, and pods) in comparison to the average weight obtained in the other cultivation variants. However, the literature to date has reported that no-till systems have a beneficial effect on root development due to improved soil properties compared to conventional tillage [39,52,57].

Table 6. Dry matter yield and nitrogen content of faba bean crop residues depending on tillage system.

Treatment (Factor T)	Year of Study (Factor Y)				Average (T)
	2016	2017	2018	2019	
	Dry matter yield of faba bean residues (t ha^{-1})				
CT	7.66 c–e	8.00 bc	2.58 i	2.88 hi	5.28 BC
RT	7.74 c–e	8.27 b	2.80 hi	3.05 h	5.46 AB
ST	7.91 b–d	8.72 a	2.92 hi	3.01 h	5.64 A
NT	6.21 g	6.81 f	2.95 hi	3.13 h	4.78 C
Average (Y)	7.38 B	7.95 A	2.81 C	3.02 C	-
	Nitrogen content of faba bean residues (kg N ha^{-1})				
CT	109.4 ab	109.1 ab	43.3 g	42.1 g	76.0 BC
RT	107.2 ab	108.8 ab	47.1 e–g	44.3 fg	76.8 AB
ST	107.2 ab	111.7 a	48.7 ef	43.7 g	77.8 A
NT	83.4 d	93.6 c	49.8 e	45.2 e–g	68.0 D
Average (Y)	101.8 B	105.8 A	47.2 C	43.8 D	-

CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; values marked with the same capital letters (Y and T separately) and lower case letters (Y and T interaction) are not significantly different at $p = 0.05$.

The nitrogen accumulation in post-harvest residues varied depending on the tillage system and the pattern of moisture and thermal conditions during the faba bean growing season (Table 6). The amount of nitrogen supplied to the soil in the faba bean post-harvest residues ranged from 43.8 to 47.2 kg ha^{-1} in dry years (2019 and 2018) and 101.8 to 105.8 kg ha^{-1} in wet years (2016 and 2017). The impact of tillage systems on nitrogen accumulation in faba bean post-harvest residues varied among the study years. In wet years, direct drilling resulted in a lower nitrogen accumulation in post-harvest residues compared to other tillage options. In dry years, no such relationship was recorded. In 2019, the year with the least favorable moisture conditions, the highest nitrogen accumulation was found in direct sowing. Moreover, it should be noted that the disparities in nitrogen accumulation in faba bean post-harvest residues among various tillage systems were not always substantiated statistically. The amount of nitrogen left in faba bean post-harvest residues plays an important role in fertilizing successive crops, although there is a risk of too rapid mineralization in the soil because of the narrow C/N ratios [14].

3.4. Correlation Coefficients of the Faba Bean Features

The analysis indicates a lack of correlation between density and other properties for CT and RT (Table 7). In the case of ST, no correlation was found between density and TGW and seeds, compared to NT. For the majority of the traits examined, there was a strong correlation between them, ranging from moderate to severe.

Table 7. Correlation coefficients of the faba bean features depending on the tillage systems.

Year	Properties	Density	Seed Yield	TSW	Pods	Seeds in Pod	Residues	N in Residues	Protein Yield
* CT	Density (no. m^{-2})	1.00	0.29	−0.13	0.23	−0.18	0.15	0.08	0.25
	Seeds yield (t ha^{-1})	0.29	1.00	0.87 *	0.99 *	0.84 *	0.98 *	0.97 *	0.99 *
	TSW (g)	−0.13	0.87 *	1.00	0.89 *	0.92 *	0.95 *	0.96 *	0.89 *
	Pods (no. plant^{-1})	0.23	0.99 *	0.89 *	1.00	0.83 *	0.98 *	0.98 *	0.98 *
	Seeds (no. pod^{-1})	−0.18	0.84 *	0.92 *	0.83 *	1.00	0.90 *	0.92 *	0.85 *
	Residues (t ha^{-1})	0.15	0.98 *	0.95 *	0.98 *	0.90 *	1.00	0.99 *	0.98 *
	N in residues (kg ha^{-1})	0.08	0.97 *	0.96 *	0.98 *	0.92 *	0.99 *	1.00	0.97 *
	Protein yield (kg ha^{-1})	0.25	0.99 *	0.89 *	0.98 *	0.85 *	0.98 *	0.97 *	1.00
RT	Density (no. m^{-2})	1.00	0.35	0.04	0.28	−0.16	0.30	0.25	0.29
	Seeds yield (t ha^{-1})	0.35	1.00	0.83 *	0.99 *	0.78 *	0.98 *	0.98 *	0.99 *
	TSW (g)	0.04	0.83 *	1.00	0.81 *	0.79 *	0.90 *	0.92 *	0.82 *
	Pods (no. plant^{-1})	0.28	0.99 *	0.81 *	1.00	0.77 *	0.97 *	0.96 *	0.98 *
	Seeds (no. pod^{-1})	−0.16	0.78 *	0.79 *	0.77 *	1.00	0.79 *	0.83 *	0.81 *
	Residues (t ha^{-1})	0.30	0.98 *	0.90 *	0.97 *	0.79 *	1.00	0.99 *	0.97 *
	N in residues (kg ha^{-1})	0.25	0.98 *	0.92 *	0.96 *	0.83 *	0.99 *	1.00	0.97 *
	Protein yield (kg ha^{-1})	0.29	0.99 *	0.82 *	0.98 *	0.81 *	0.97 *	0.97 *	1.00
ST	Density (no. m^{-2})	1.00	0.66 *	0.21	0.63 *	0.13	0.59 *	0.53 *	0.63 *
	Seeds yield (t ha^{-1})	0.66 *	1.00	0.82 *	0.99 *	0.80 *	0.99 *	0.98 *	0.99 *
	TSW (g)	0.21	0.82 *	1.00	0.80 *	0.85 *	0.89 *	0.91 *	0.85 *
	Pods (no. plant^{-1})	0.63 *	0.99 *	0.80 *	1.00	0.80 *	0.97 *	0.97 *	0.99 *
	Seeds (no. pod^{-1})	0.13	0.80 *	0.85 *	0.80 *	1.00	0.82 *	0.86 *	0.82 *
	Residues (t ha^{-1})	0.59 *	0.99 *	0.89 *	0.97 *	0.82 *	1.00	0.99 *	0.99 *
	N in residues (kg ha^{-1})	0.53 *	0.98 *	0.91 *	0.97 *	0.86 *	0.99 *	1.00	0.99 *
	Protein yield (kg ha^{-1})	0.63 *	0.99 *	0.85 *	0.99 *	0.82 *	0.99 *	0.99 *	1.00
NT	Density (no. m^{-2})	1.00	−0.16	−0.59 *	−0.27	−0.63 *	−0.33	−0.34	−0.21
	Seed yield (t ha^{-1})	−0.16	1.00	0.80 *	0.99 *	0.83 *	0.97 *	0.97 *	0.99 *
	TSW (g)	−0.59 *	0.80 *	1.00	0.86 *	0.88 *	0.89 *	0.86 *	0.83 *
	Pods (no. plant^{-1})	−0.27	0.99 *	0.86 *	1.00	0.87 *	0.98 *	0.98 *	0.99 *
	Seeds (no. pod^{-1})	−0.63 *	0.83 *	0.88 *	0.87 *	1.00	0.90 *	0.92 *	0.86 *
	Residues (t ha^{-1})	−0.33	0.97 *	0.89 *	0.98 *	0.90 *	1.00	0.99 *	0.98 *
	N in residues (kg ha^{-1})	−0.34	0.97 *	0.86 *	0.98 *	0.92 *	0.99 *	1.00	0.98 *
	Protein yield (kg ha^{-1})	−0.21	0.99 *	0.83 *	0.99 *	0.86 *	0.98 *	0.98 *	1.00

CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; * significant at p = 0.05.

3.5. Nodules of Faba Bean Roots

During the bean growing season, the favorable pattern of moisture conditions favoured greater nodulose on bean roots (Table 8). In wet years, nodulose was twice as high as it was in dry years. In all years of the study, a higher dry weight of nodulose on faba bean roots was found in the no-inversion variants, especially in NT. It was twice as high in NT as it was in the faba bean in conventional tillage. The results obtained are consistent with those of the other authors [39,57].

Table 8. Dry weight of nodules of faba bean roots, g plant^{-1}.

Treatment (Factor T)	Years (Factor Y)				Average (T)
	2016	2017	2018	2019	
CT	0.16 c	0.35 b	0.09 c	0.09 c	0.17 C
RT	0.29 b	0.41 ab	0.19 ab	0.17 b	0.26 B
ST	0.34 ab	0.37 ab	0.20 ab	0.18 ab	0.27 B
NT	0.35 a	0.44 a	0.23 a	0.21 a	0.31 A
Average	0.29 B	0.39 A	0.18 C	0.16 C	-

CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; values marked with the same capital letters (Y and T separately) and lower case letters (Y and T interaction) are not significantly different at $p = 0.05$.

3.6. Soil Physical Properties

Non-inversion tillage, and especially NT, resulted in increased soil moisture in the 0–10 and 10–20 cm layer, compared to the moisture recorded in CT, which is important for the development of faba bean in years with rainfall deficiencies (Table 9). Conversely, the elimination of ploughing has been shown to result in an increase in soil bulk density and a reduction in the capillary water capacity of the soil in the surface layer (up to 10 cm), which has the potential to limit faba bean growth and development during the early growing season. In contrast, in the deeper layer (10–20 cm), soil properties are conducive to plant development in NT systems compared to CT. However, it is important to note that long-term experimentation has demonstrated that the implementation of no-till systems over an extended period results in a notable enhancement of the soil's physical characteristics, a phenomenon attributable to the activity of soil fauna, leading to the formation of biogenic pores, primarily in a vertical orientation [5,34,36]. Consequently, in years characterized by adverse weather conditions, higher yields of faba bean are observed in systems that employ RT, and occasionally, in NT, as compared to CT methods.

Table 9. Physical properties of soil after faba bean harvest (average 2016–2019).

Treatment	Volumetric Water Content %		Bulk Density Mg m^{-3}		Capillary Water Capacity %	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
CT	14.1 c	16.7 c	1.44 c	1.66 a	35.6 a	30.1 b
RT	15.6 b	17.9 b	1.55 ab	1.56 b	32.9 b	33.1 a
ST—in raw	14.7 c	16.5 c	1.46 c	1.54 b	36.6 a	33.2 a
ST—inter-raw	15.9 ab	18.8 a	1.57 ab	1.58 ab	30.6 c	31.9 ab
NT	16.4 a	18.4 ab	1.60 a	1.54 b	31.6 bc	32.7 a

CT—conventional tillage; RT—reduced tillage; ST—strip-tillage; NT—no-tillage; values marked with the same letters in columns are not significantly different at $p = 0.05$.

3.7. Soil Chemical Properties

The direction of the changes in the chemical properties of the soil, influenced by the long-term effect of CT and RT and NT, is consistent with the results of long-term experiments by other authors [63]. In non-inversion tillage, particularly in NT, there was an increased accumulation of organic carbon in the 0–10 cm soil layer in comparison to ploughing, while in the 10–20 cm layer the relationships were the opposite (Table 10).

Analogous relationships were observed for total nitrogen and the C:N ratio in the 0–10 cm soil layers. The tillage variants did not demonstrate a significant difference in total nitrogen content or the C:N ratio within the 10–20 cm layer. The content of available phosphorus in the soil remained unaltered by the tillage systems. However, the content of available forms of potassium and magnesium in the soil (up to a depth of 10 centimeters) was higher in NT systems than in CT systems. The investigation revealed that the content of available potassium and magnesium was consistent across the three tillage variants in the deepest soil layer analyzed.

Table 10. Chemical properties of soil before the start of research (2016).

Parameter	Treatment	Soil Layer (cm)	
		0–10	10–20
C organic ($g\ kg^{-1}$)	CT	7.62 c	7.87 a
	RT	9.02 b	7.70 ab
	NT	10.64 a	7.40 b
N total ($g\ kg^{-1}$)	CT	0.93 c	0.91 a
	RT	1.02 b	0.88 a
	NT	1.10 a	0.86 a
C/N	CT	8.2 c	8.6 a
	RT	8.9 b	8.7 a
	NT	9.7 a	8.6 a
P ($mg\ kg^{-1}$)	CT	208 a	203 a
	RT	198 a	206 a
	NT	199 a	213 a
K ($mg\ kg^{-1}$)	CT	141 c	145 a
	RT	182 a	133 a
	NT	196 a	134 a
Mg ($mg\ kg^{-1}$)	CT	27.8 c	29.3 a
	RT	41.8 b	27.7 a
	NT	53.7 a	20.5 a

CT—conventional tillage; RT—reduced tillage; NT—no-tillage; values marked with the same letters are not significantly different at $p = 0.05$.

4. Conclusions

Low profitability of leguminous crops cannot be the only criterion for the purpose of their cultivation because they provide a number of important so-called "ecosystem services". Promoting the cultivation of this group of plants is important due to increased biodiversity and environmental aspects. In the case of wheat or rapeseed grown after leguminous crops, the costs of nitrogen fertilization are reduced. Therefore, the profitability of plants should be considered in the context of the entire crop rotation and not just individual species.

The weather conditions had a greater impact on faba bean yields than the different tillage systems used. In years with low rainfall and high air temperature during the bean growing season, which further aggravated the soil drought, seed yield was 3–4 times lower than in years with favorable moisture conditions. The differences in faba bean seed yields between different tillage systems were primarily determined by plant density and, to a lesser extent, other yield components.

The research took place in two extremely different weather conditions. Two very favorable years and two with catastrophic drought. This allowed for the assessment of the production effects of the tested agricultural systems in different conditions, i.e., their sustainability. Slight differences were noted in faba bean yields between CT, RT, and ST, while NT reduced the yields of these variants in wet years. On the contrary, in extremely dry years, NT was more favorable than CT. In all years of the study, higher dry weight of nodulose on faba bean roots was found in the no-inversion variants, especially in NT. Non-inversion tillage, and especially NT, resulted in increased soil moisture in the 0–10 and 10–20 cm layer, compared to the moisture recorded in CT, which is important for the development of faba bean in years with rainfall deficiencies. In non-inversion tillage, particularly in NT, there was an increased accumulation of organic carbon in the 0–10 cm soil layer in comparison to ploughing.

Considering the sustainability of the assessed tillage systems in faba bean, both in terms of environment and production, RT and ST should be indicated as the most sustainable. They make it possible to keep part of the mulch on the ground surface and limit the intensity of tillage, and can be classified as conservation tillage, as opposed to conventional tillage. NT provides the best soil protection and conservation, but in favorable weather conditions, it limits the yield level of faba beans. The yields obtained in RT and ST technologies were high, both in favorable and extremely unfavorable years. Given the increasing climatic instability and unpredictable weather, yield stability in various conditions is as important as ensuring conservation tillage.

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