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Influence of genetic potential of soybean hybrids and soil tillage on physical and biochemical yield quality traits

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Optimizing soybean production in the context of climate change and soil fertility degradation requires a balanced approach that integrates advanced breeding outcomes with efficient soil management practices. This study addresses the need for sustainable technological strategies that maximize both grain yield and biochemical quality under varying agroecological conditions. The article investigates the influence of primary soil tillage methods and the genetic potential of modern soybean hybrids on yield, 1,000-seed weight, and biochemical quality traits. Field experiments were conducted in 2024–2025 on weakly acidic soils with low organic matter content in Chernihiv Oblast, Ukraine. The design included four tillage methods (moldboard plowing to 22 cm, deep loosening to 27 cm, subsurface tillage to 22 cm, and double–disk harrowing to 14 cm) and three soybean hybrids (Arcadia, Apica, and Mentor). Biochemical analysis involved determining crude protein content using the Kjeldahl method and oil content using Soxhlet extraction. The experimental results revealed that the 1,000-grain weight varied between 157.00 and 180.50 g. Crop yield was also significantly affected by the factors. The hybrid Apica formed the highest average yield of 3.12 t/ha, significantly outperforming Arcadia (2.83 t/ha) and Mentor (2.73 t/ha). Conventional plowing resulted in the highest average yield of 3.04 t/ha, while disk harrowing decreased it to 2.77 t/ha. The combination of plowing and the hybrid Apica provided the maximum yield of 3.27 t/ha, significantly exceeding disk harrowing with Mentor (2.60 t/ha). For biochemical traits, plowing maximized crude protein (40.18%) and oil content (20.52%), while disk harrowing significantly reduced protein to 39.03% and oil to 19.62%. The hybrid Apica accumulated the highest protein content (40.65%), while Arcadia demonstrated a strong genetic predisposition to lipid synthesis, reaching a maximum oil content of 21.30%. In conclusion, maximizing soybean productivity and quality requires combining conventional deep plowing with highly adaptive hybrids such as Apica.

Keywords: *Glycine max*; agrotechnology; crop yield; protein; oil content; 1,000-seed weight.

Introduction

Soybean (*Glycine max* L.) is one of the most promising agricultural crops, holding strategic importance for ensuring global food security. The exceptional relevance of this crop is primarily due to its unique nutritional value and versatility of use. Soybean occupies a leading position in the global balance of plant protein due to its high content of protein and lipids, balanced amino acid composition, and the presence of vital macro- and microelements, features that are rarely found in other cereal or leguminous crops (Alarape et al., 2024).

Another aspect that characterizes soybean as an indispensable crop in crop rotation is its capacity for atmospheric nitrogen fixation. Specifically, this ability is realized through the symbiosis of plants with nodule bacteria. Due to this biological feature, soybean not only minimizes the need for mineral nitrogen fertilizers, which significantly reduces the energy intensity of production, but also substantially improves soil fertility for subsequent crops in the rotation (Tryus et al., 2026a). An effective symbiosis contributes to the accumulation of available forms of nitrogen in the soil, which remains in postharvest residues and becomes an important factor in optimizing the nitrogen nutrition of the agrocoenosis. Under modern conditions of agricultural ecologization and rising energy prices, the ability of soybean to fix nitrogen transforms it into a strategic tool for increasing the profitability and stability of agricultural production, allowing for a harmonious combination of high productivity with the principles of regenerative agriculture.

The application of modern breeding strategies, particularly the use of male sterility systems and molecular marking methods, opens new opportunities for creating high-yielding soybean hybrids with improved characteristics. Although the self-pollinating nature of the crop and the limitation of natural cross-pollination pose certain technological challenges, the successful experience of implementing "three-line" breeding in China confirms the reality of commercial hybrid production. The integration of functional genomics tools and genome editing into the breeding process will allow for the development of more stable technologies for hybrid seed production, which is critically important for increasing soybean productivity on a global scale (Chandra et al., 2022). The efficiency of realizing the genetic potential of soybean largely depends on the interaction of additive gene effects of parental forms, which determine the main elements of yield structure. Research by Mazur (2023) confirms that the breeding value of hybrid combinations, such as Sawyer 2-95 x Hoverla or Kyivska 97 x Hoverla, is due to the manifestation of overdominance and nonadditive gene interaction. The use of such forms in crossbreeding programs makes it possible to predictably increase productivity indicators and yield stability under specific agroclimatic conditions.

Assessing the realized genetic gain of quantitative traits in soybean, particularly yield, remains a challenging task due to the significant influence of variable environmental factors and agrotechnological practices. The work of Krause et al. (2023) analyzes the effectiveness of using linear mixed models to evaluate breeding progress, with the authors pointing out the potential bias of results when relying on only a single statistical approach. Based on the data modeling over a thirty-year period, the study demonstrates real yield growth and highlights the necessity of a comprehensive assessment using multiple models to minimize errors. Meanwhile, the results of Khan et al. (2022) focus on evaluating the genetic diversity of 20 soybean genotypes through the analysis of nine morphological traits using Mahalanobis D2 statistics. Based on cluster analysis, the authors identified the most divergent groups of genotypes, which serves as a key tool for planning effective hybridization strategies aimed at increasing productivity. The obtained results confirm that selecting parental forms with maximum genetic distances allows for the maximization of the heterotic effect and the improvement of breeding parameters in new varieties. The study by Bhuiyan et al. (2024) demonstrates the effectiveness of the gamma-radiation-induced mutagenesis method as a tool to overcome the genetic bottleneck and increase soybean yield under the conditions of Bangladesh. The application of a 250 Gy dose allowed for the isolation of a promising mutant, SBM-18, which demonstrated the highest yield stability and adaptability across different agroecological zones. Due to high yield indicators (up to 3,056 kg/ha) and improved morphological traits, this mutant was officially registered as the Binasoybean-5 variety for commercial cultivation. This work emphasizes that targeted breeding of mutant lines with high hereditary variation is a promising path toward creating high-yielding varieties that are more economically efficient than traditional counterparts. Breeders are constantly searching for a balance between yield quantity and quality, as soybean has become more high–yielding over recent decades but has, at the same time, lost a significant amount of its protein level. The use of new mathematical selection methods (FAI-BLUP and GYT Biplot) helps scientists simultaneously increase plant productivity and halt the decline of nutrient content in the grain. Thanks to this approach, it is possible to breed varieties that not only produce high yields but also retain high nutritional and feed qualities (Ferreira et al., 2025).

Despite significant successes in the genetic improvement of the crop through hybridization and mutagenesis, the realization of the full potential of newly developed genotypes is impossible in isolation from cultivation conditions. Genetic achievements are merely a foundation, the effectiveness of which directly depends on the environment, where agrotechnology serves as a key factor. In particular, the choice of soil tillage strategy determines not only the availability of moisture and nutrients for the root system but also the level of plant interaction with the microbiome, which is critical for obtaining stably high yields and maintaining soil fertility under changing climatic conditions. Thus, studies by Chețan et al. (2022) indicate that the choice of soil tillage technology significantly determines the phytosanitary state of soybean crops and their productivity. Specifically, conventional moldboard plowing provides better weed control, whereas the transition to minimal or zero tillage leads to increased competition from weeds and is accompanied by a decrease in crop yield. Analyzing the impact of different soil tillage systems, it should be noted that conventional plowing provides the most favorable conditions for the development of the photosynthetic apparatus of soybean, which manifests in higher indicators of leaf area index and chlorophyll content compared with minimal and zero tillage systems (Buczek et al., 2022). The efficiency of photosynthetic functioning in the conventional tillage system is confirmed by higher values of chlorophyll fluorescence parameters. Although minimal and zero tillage systems demonstrate higher water-use efficiency, which can be a strategic advantage under drought conditions, they generally fall short of the conventional system in terms of yield level and seed protein content. The results of the study by Gawęda et al. (2014) show that conventional plowing provides a 14.7% higher soybean yield than direct sowing, which is due to a better crop density. At the same time, the variety Aldana demonstrated higher productivity than Augusta due to a greater 1,000-seed weight and higher plant density indicators before harvesting.

The objective of this study was to comprehensively evaluate the interaction between the genetic potential of modern soybean hybrids and various primary soil tillage methods to determine their combined influence on crop productivity, seed biochemical quality, and the realization of adaptive potential under the specific agroclimatic conditions of Northern Ukraine. This research aims to identify optimal technological combinations that enhance yield stability and nutrient composition, providing evidence-based recommendations for sustainable soybean production.

Materials and methods

Field studies were conducted during 2024–2025 on a farm located in the village of Vertiivka, Nizhyn District, Chernihiv Oblast. The soil of the experimental plot is characterized by a weakly acidic reaction (pH 5.5–5.9) and a low organic matter content (1.3–2.2%). Soil agrochemical analysis indicates the following level of nutrient availability: nitrate nitrogen content is 3–6 mg/kg, phosphorus is 68–116 mg/kg, potassium is 109–142 mg/kg, calcium (Ca) is 664–1533 mg/kg, and magnesium (Mg) is 63–145 mg/kg. Climatic conditions during the research period were characterized by significant variability of hydrothermal indicators, which is typical for current climate change trends in the region. Analysis of meteorological data indicates an overall elevated temperature background and an extremely uneven distribution of precipitation throughout the growing season (Fig. 1).

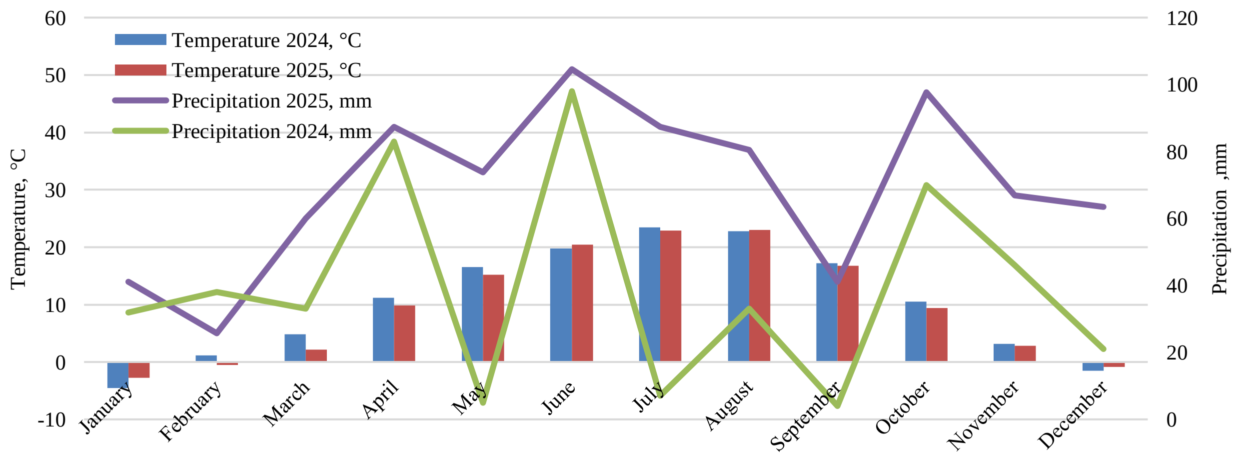

Fig. 1. Climatic conditions for soybean cultivation in 2024–2025 (Nizhyn District, Chernihiv Oblast)

The 2024 growing season was characterized by a high amplitude of fluctuations in both temperatures and precipitation. The sowing campaign and initial growth stages took place under conditions of sharp contrast: an excessively wet April (83 mm of precipitation) was followed by a critically dry May, during which only 5 mm of precipitation fell at an average monthly temperature of 16.5 °C. June brought a significant amount of precipitation (98 mm) against the background of a temperature increase to 19.8 °C, which stimulated active accumulation of vegetative mass. However, the middle and end of summer were accompanied by a severe drought. In July and August, average monthly temperatures reached peak values of 23.4 and 22.8 °C, respectively, while precipitation was only 7 mm in July and 33 mm in August. September also turned out to be abnormally dry (4 mm of precipitation), which triggered premature termination of vegetation and a reduction in the crop productivity potential.

In 2025, the hydrothermal regime was somewhat more stable in the first half of summer, but it was also characterized by a moisture deficit in the second half of the growing season. The spring period was marked by moderate temperatures and precipitation (41 mm in April, 33 mm in May). June provided the crops with 51 mm of precipitation at an average temperature of 20.4 °C. In July and August, the temperature background remained consistently high, amounting to 22.9 and 23.0 °C, respectively. The amount of precipitation in these months (41 and 37 mm) was higher compared to the same period of the previous year, yet it remained insufficient to fully meet the needs of soybean during intensive seed filling. September, with an average temperature of 16.8 °C and a small amount of precipitation (14 mm), caused rapid drying of plants before harvesting, but intensified the overall stress from lack of moisture at the end of the developmental cycle.

The field experiment design involved studying the effects of four primary soil tillage methods on the productivity of different soybean hybrids from various originators (Table 1). The arrangement of variants was carried out using a systematic layout method in four replications; the area of the record plot was 2 ha. Agrotechnical practices complied with the generally accepted recommendations for this region.

Table 1
Experimental design layout

Factor A: Primary soil tillage method	Factor B: Soybean hybrid	Originator
1. Deep loosening to 27 cm (STROM LINE–1.2)	Arcadia	Saatbau
2. Disk harrowing to a depth of 14 cm in two passes (BDT–7)	Apica	Prograin
3. Subsurface tillage to a depth of 22 cm (KPG–2–150)	Mentor	Lidea
4. Moldboard plowing to a depth of 22 cm (control, PLN-4–35)	–	–

To evaluate individual soybean productivity, sample sheaves were collected from each experimental variant prior to harvesting. Harvesting was performed by direct combining, with the yield recorded for each individual plot and seed material sampled for subsequent laboratory analyses. Grain size was evaluated based on the 1,000-seed weight in accordance with DSTU 2949. Analysis of yield quality characteristics included the determination of protein content (by the Kjeldahl method) and fat content (via extraction by the Soxhlet method).

For a detailed pairwise comparison of mean values between individual experimental variants, determining the significance of differences between them, and forming homogeneous groups, Tukey's Honestly Significant Difference (Tukey's HSD) post-hoc comparison test was applied. The significance of differences between the samples was evaluated at the critical significance level of $P < 0.05$, which is conventionally accepted in agronomic research. All stages of statistical analysis, including the calculation of descriptive statistics, means, standard deviations (SD), and the construction of probability matrices for post-hoc tests, were performed using Statistica 10.0 software (StatSoft Inc., Tulsa, USA).

Results

The analysis of the research results indicates that the 1,000-seed weight of soybean varied depending on the primary soil tillage methods and the biological characteristics of the studied genotypes (Table 2), demonstrating a clear trend favoring conventional plowing (control). The highest seed size values were recorded in the plowing variant. Depending on the hybrid, the 1,000-seed weight ranged from 171.5 to 180.5 g. The application of noninversion and surface tillage methods led to a gradual decrease in this indicator. Specifically, with deep loosening, the 1,000-seed weight was 165.0–174.0 g; with subsurface tillage, it was 161.0–170.0 g; and the minimum values in the experiment were recorded in the disk harrowing variants, where the parametr decreased to 157.0–167.0 g. Regarding varietal characteristics, the Arcadia hybrid consistently outperformed others across all tillage variants, producing the most well-filled seeds, whereas the Mentor hybrid exhibited lower performance than the other studied samples.

Mathematical justification of the obtained experimental data using analysis of variance showed that the observed differentiation in 1,000-seed weight is not statistically significant. The obtained Fisher's criterion value ($F = 0.96$) and the calculated significance level ($P = 0.49$), which significantly exceeds the critical threshold conventionally accepted in agronomic research ($P > 0.05$), indicate the absence of a mathematically significant effect of soil tillage factors, genotype, or their interaction on the studied trait. Multiple pairwise comparisons of mean values using Tukey's HSD test confirmed high variability of the indicator within replications, as even for the most distant variants (Plowing Arcadia and Disking Mentor), the error probability level was $P = 0.45$. As a result of statistical grouping, all 12 factor combinations were included in one homogeneous group, which indicates the random nature of the observed differences and the equivalence of the studied variants regarding this structural indicator.

The analysis of soybean yield results indicates a pronounced variability of this indicator depending on the studied soil tillage factors and the genetic characteristics of the hybrids. The highest productivity levels were recorded in the control variant using conventional plowing, where the average yield reached maximum values in the experiment. By contrast, the minimum grain yield indicators were observed under conditions of surface tillage, specifically disk harrowing. Among the studied varietal composition, the Apica hybrid stood out clearly, demonstrating consistently high adaptability and productivity under all soil tillage methods, whereas the Arcadia and Mentor hybrids formed significantly lower yield indicators.

Mathematical evaluation of the obtained data set using multifactorial analysis of variance confirmed the statistical significance of the studied effects. The calculated Fisher's criterion value was $F = 2.396$, and the obtained significance level was $P = 0.0155$, which is significantly lower than the critical threshold of 0.05. This indicates that the total variance of soybean yield is not caused by random variation but is the result of the real influence of the studied factors, namely tillage method and the biological characteristics of the hybrid.

Detailed factor-by-factor analysis using Tukey's HSD test allowed for a clear differentiation of the degree of influence of each factor separately. It was found that the hybrid factor was of decisive importance for the formation of soybean productivity levels. The Apica hybrid, with an average indicator of 3.12 t/ha, statistically significantly outperformed both the Arcadia hybrid (2.83 t/ha, $P = 0.0068$) and the Mentor hybrid (2.73 t/ha, $P = 0.0003$). At the same time, the difference between Arcadia and Mentor proved to be mathematically insignificant ($P = 0.5129$). Evaluation of the impact of primary soil tillage methods as a separate factor showed that plowing provided the highest average yield at 3.04 t/ha; however, its superiority over deep loosening (2.85 t/ha) and subsurface tillage (2.92 t/ha) did not reach the threshold of statistical significance. The greatest differentiation was observed between plowing and disk harrowing (2.77 t/ha), where the p-value was 0.0742, which can be viewed as a clear trend toward a decrease in productivity under shallow mulching tillage.

Analysis of pairwise bifactorial comparisons using Tukey's HSD test for the interaction of Tillage × Hybrid factors showed a high level of overlap of homogeneous groups, which is associated with the internal variability of the trait. The only mathematically proven difference at the significance level of $P < 0.05$ was recorded between the most contrasting variants of the experiment. The control plowing variant in combination with the Apica hybrid, which provided the maximum yield of 3.27 t/ha, statistically significantly outperformed the disk harrowing variant with the Mentor hybrid, where the lowest productivity was obtained – 2.60 t/ha ($P = 0.0266$). All other intervariant comparisons, including the comparison of plowing and noninversion tillage within the same hybrid, did not reveal mathematically significant differences, which confirms the flexibility of the crop's adaptive potential, although the general vector of superiority of deep moldboard technologies remains evident.

The analysis of crude protein accumulation in soybean seeds indicates a clear dependence of this quality indicator on both primary soil tillage methods and the biological characteristics of the studied genotypes (Table 3). The research revealed a pronounced trend toward a decrease in seed protein content as the depth and intensity of mechanical impact on the soil decreased. The application of conventional plowing ensured the maximum protein level, while the lowest values were recorded under surface tillage with disk implements. Regarding varietal characteristics, the Apica hybrid demonstrated the best ability to synthesize and deposit nitrogenous compounds in seeds, maintaining a stable lead across all technological variants, whereas the Arcadia hybrid performed significantly lower than the other studied samples.

Table 2
Indicators of 1,000-seed weight of soybean and its yield depending on primary soil tillage methods and biological characteristics of the hybrid (mean ± SD, n = 6)

Tillage method	Hybrid	Weight of 1,000 grains, g	Yield, t/ha
Plowing	Arcadia	180.5 ± 6.6^{a}	2.9 ± 0.4^{ab}
Plowing	Apica	175.5 ± 25.8^{a}	3.2 ± 0.2^{a}
Plowing	Mentor	171.5 ± 15.0^{a}	2.8 ± 0.3^{ab}
Deep Loosening	Arcadia	174.0 ± 6.1^{a}	2.7 ± 0.3^{ab}
Deep Loosening	Apica	168.5 ± 25.8^{a}	3.0 ± 0.1^{ab}
Deep Loosening	Mentor	165.0 ± 14.4^{a}	2.7 ± 0.3^{ab}
Subsurface Tillage	Arcadia	170.0 ± 6.1^{a}	2.7 ± 0.3^{ab}
Subsurface Tillage	Apica	164.0 ± 25.3^{a}	3.0 ± 0.1^{ab}
Subsurface Tillage	Mentor	161.0 ± 13.4^{a}	2.6 ± 0.3^{b}
Disking	Arcadia	167.0 ± 6.1^{a}	2.8 ± 0.3^{ab}
Disking	Apica	160.0 ± 25.3^{a}	3.1 ± 0.1^{ab}
Disking	Mentor	157.0 ± 13.4^{a}	2.7 ± 0.3^{ab}

Note: values in columns followed by different letter indexies indicate statistically significant differences at P < 0.05 (Tukey's HSD test).

Table 3
Protein and oil content in soybean seeds depending on primary soil tillage methods and biological characteristics of the hybrid (mean ± SD, n = 6)

Tillage method	Hybrid	Protein content, %	Oil content, %
Plowing	Arcadia	38.9 ± 1.7^{abc}	21.7 ± 0.6^{a}
Plowing	Apica	41.3 ± 0.3^{d}	20.0 ± 0.5^{bc}
Plowing	Mentor	40.3 ± 0.3^{bcd}	19.8 ± 0.3^{cd}
Deep Loosening	Arcadia	38.3 ± 1.7^{ab}	21.4 ± 0.6^{a}
Deep Loosening	Apica	40.7 ± 0.3^{cd}	19.7 ± 0.5^{cd}
Deep Loosening	Mentor	39.7 ± 0.3^{abcd}	19.5 ± 0.3^{cd}
Subsurface Tillage	Arcadia	38.0 ± 1.7^{a}	21.1 ± 0.6^{a}
Subsurface Tillage	Apica	40.4 ± 0.3^{cd}	19.4 ± 0.5^{cd}
Subsurface Tillage	Mentor	39.5 ± 0.3^{abcd}	19.2 ± 0.3^{cd}
Disking	Arcadia	37.7 ± 1.7^{a}	20.8 ± 0.6^{ab}
Disking	Apica	40.1 ± 0.3^{bcd}	19.1 ± 0.5^{cd}
Disking	Mentor	39.2 ± 0.3^{abc}	18.9 ± 0.3^{d}

Mathematical justification of the obtained results using Tukey's HSD test allowed for a detailed assessment of the significance of differences between individual levels of the soil tillage factor. A statistically significant difference at a high confidence level was found only when comparing the conventional plowing variants (mean protein content of 40.18%) and surface disk harrowing (39.03%), where the error probability value was P = 0.0089, which is significantly lower than the critical threshold of 0.05. Comparing plowing with noninversion subsurface tillage (39.33%) indicates a noticeable biological trend toward differentiation, as the obtained value of P = 0.0815 approaches the significance limit. All other pairwise comparisons between minimized and noninversion technologies (specifically between deep loosening (39.58%), subsurface tillage, and disk harrowing) showed the absence of mathematically proven differences (P > 0.05), which confirms the similarity of conditions for grain quality formation when abandoning moldboard tillage.

Evaluation of the genotype factor influence using Tukey's HSD test revealed a deep and comprehensive statistical significance of differences between all studied soybean hybrids. It was established that the Apica hybrid, with an absolute mean protein content of 40.65%, significantly outperformed both the Mentor hybrid (39.70%, P = 0.0074) and the Arcadia hybrid (38.25%, P = 0.0001). In turn, the Mentor hybrid also showed a significant mathematical advantage over the Arcadia hybrid in terms of protein accumulation in seeds, where the probability level of the random nature of differences was practically equal to zero (P = 0.0001). Thus, the biological potential for protein accumulation completely differentiated the studied genotypes into three entirely separate, nonoverlapping homogeneous groups, which confirms the leading role of the genetic factor in forming the quality indicators of the crop harvest.

The analysis of oil accumulation in soybean seeds showed a clear and consistent reaction of this indicator to both changes in soil tillage methods and the genetic characteristics of the studied hybrids. A pronounced trend toward a decrease in seed oil content is observed when mechanical tillage is minimized: maximum indicators are ensured by conventional plowing, while the transition to surface disk harrowing leads to a noticeable depletion of fats in the seeds. In terms of varieties, an absolute leader for this trait was identified – the Arcadia hybrid, which significantly outperformed other breeding samples in oil content, while the Apica and Mentor hybrids demonstrated results that are quite close to each other.

Mathematical justification of the results using Tukey's HSD test allowed for a clear separation of soil tillage methods by their influence on oil content. It was established that conventional plowing (mean fat content of 20.52%) ensures a statistically significantly higher level of oiliness compared with subsurface tillage (19.92%, P = 0.0057) and surface disk harrowing (19.62%, P = 0.0002). In addition, the deep loosening variant (20.22%) also mathematically provenly outperforms the disk harrowing variant (P = 0.0057). At the same time, the difference between technologies adjacent in intensity (plowing and deep loosening, deep loosening and subsurface tillage, as well as subsurface tillage and disk harrowing) proved to be statistically imperceptible (in all cases P = 0.3213), which indicates a gradual, evolutionary nature of the decrease in grain quality when simplifying the tillage system.

Evaluation of the genotype factor effect using Tukey's HSD post–hoc test confirmed a high degree of differentiation between the studied soybean hybrids. The Arcadia hybrid, with a mean oil content indicator of 21.30%, formed a separate, highly significant leader group, which mathematically significantly outperforms both the Apica hybrid (19.55%, P = 0.0001) and the Mentor hybrid (19.35%, P = 0.0001). In turn, when comparing the indicators between Apica and Mentor, no statistically proven difference was found (P = 0.3866). This indicates that, regarding the ability to synthesize and deposit lipids in seeds, these two hybrids belong to one homogeneous group and have similar biological oil–producing potential under the conditions of the experiment.

Discussion

Conventional plowing proved to be the best option for most indicators, as it completely turns over the soil layer. This helps to distribute nutrients evenly, improves air access to the roots, and activates beneficial bacteria. As a result, soybean plants more efficiently absorb nitrogen, which directly influences the formation of higher yields and protein accumulation in the seeds.

Accordingly, when a farm switches to shallower tillage methods, such as disk harrowing, conditions for the plants deteriorate. Nutrients remain only in the top layer, and deeper soil layers become too dense for root growth. Furthermore, moisture evaporates more intensely from the surface. Consequently, plants lack water and nutrition during critical periods of vegetation, leading to a decrease in yield, oil content, and protein quantity.

The study clearly confirmed that different soybean hybrids have their own biological peculiarities regarding nutrient accumulation. The Apica hybrid directs its resources toward forming a large amount of grain and protein, which is why it became the leader in yield. By contrast, the Arcadia hybrid is genetically predisposed to lipid synthesis; therefore, its seeds had maximum oil content but were inferior to others in terms of protein content. The Mentor hybrid occupied an intermediate position between them.

An interesting situation occurred with the 1,000-seed weight. Although the figures in the tables differed noticeably between variants, the mathematical analysis showed that these discrepancies were random. This indicator depends heavily on weather during soybean maturation and minor differences across various parts of the field, so the tillage method or the choice of hybrid did not have a decisive systematic influence on it in this experiment.

The best results in agriculture are obtained when efficient technology is combined with the right variety. In our case, the combination of deep plowing and the productive Apica hybrid yielded the highest harvest. This proves that to achieve maximum productivity, the field tillage method must be selected individually according to the biological characteristics of the specific soybean hybrid.

Such statements are also supported by the results of other scientists. In particular, the results obtained regarding the superiority of conventional tillage are consistent with the conclusions of a large-scale 50-year study (Ordóñez et al., 2025), in which standard deep plowing also provided higher soybean yield indicators in most years compared with minimal tillage systems. At the same time, the authors note that although no-till farming was inferior in absolute yield, it demonstrated better ecological sustainability and yield stability under conditions of prolonged spring warming. Similar patterns regarding the impact of tillage minimization on seed quality parameters are described by Faligowska et al. (2025), who note that abandoning conventional plowing in favor of no-till or reduced tillage can lead to a decrease in 1,000-seed weight and soybean germination. However, in their study, no-till demonstrated high adaptability in unfavorable dry years, ensuring yield stability and a higher content of mineral substances in seeds due to better preservation of soil structure. Long-term modeling of agroecosystems, conducted by Huang et al. (2022), also confirms that no-till systems have only a negligible impact on soybean yield variability compared with traditional intensive methods. At the same time, the researchers emphasize the significant ecological advantages of minimized technologies, which significantly reduce greenhouse gas emissions, particularly carbon dioxide and nitrogen oxide, while simultaneously increasing the overall stability of agricultural production. This indicates that the implementation of gentle noninversion methods allows for the successful combination of ecological sustainability of agrocoenoses with the maintenance of an appropriate level of crop productivity. The results obtained by Tryus et al. (2026b) demonstrate that the systematic use of Rhizogumin, especially when combined with foliar treatments, significantly intensifies symbiotic activity and optimizes yield structure components, such as the number of pods and seeds per plant. While these biological preparations substantially improve key physiological indicators, their final contribution to productivity remains sensitive to abiotic stress factors, which can partially negate the potential yield increase. Consequently, the synergy between seed inoculation and targeted foliar nutrition represents a critical pathway for enhancing crop resilience and achieving stable productivity in fluctuating climatic conditions.

The results of our study, where the tillage method showed a limited impact on protein content only between the most contrasting variants, resonate with the conclusions of Epie et al. (2023). The researchers note that tillage technologies often do not have a decisive or stable influence on the chemical composition of soybean seeds, whereas other factors of agrocoenosis regulation, particularly sowing density, are more effective for increasing protein concentration. This further confirms that final grain protein content depends more on internal biological factors and the optimization of crop structure than on the soil loosening method alone. By contrast, Adekiya et al. (2024) emphasize the importance of the physical state of the soil environment, noting that optimizing tillage through plowing with harrowing significantly reduces bulk density and increases soil porosity. Such loosening promotes more active root growth and efficient nutrient uptake, leading to a noticeable increase in yield, as well as an increase in the concentration of protein, fat, and mineral substances in soybean seeds. At the same time, the researchers point out that even with a high content of organic matter and nutrients in no–till variants, the increased density of unloosened soil becomes the main limiting factor that does not allow the crop to fully realize its productive and qualitative potential.

Conclusion

Summarizing the research results indicates that primary soil tillage methods and the genetic characteristics of soybean hybrids have a decisive, often interrelated influence on the formation of yield and biochemical indicators of seed quality, whereas their effect on 1,000-seed weight is random due to the high sensitivity of this trait to abiotic vegetation conditions. Conventional plowing provides an optimal agrophysical background, which guarantees the highest average yield of 3.04 t/ha, a crude protein content of 40.18%, and an oil content of 20.52%, while simplifying the technology to surface disk harrowing leads to a systematic deterioration of productivity and biochemical grain parameters. Regarding varietal characteristics, a clear genetic determination and an inverse correlation between the accumulation of nitrogenous compounds and lipids were confirmed: the Apica hybrid is the leader in grain yield (3.12 t/ha) and protein content (40.65%), while Arcadia maximally realizes its potential for fat synthesis (21.30%). The synergistic effect of the interaction of these factors manifested most fully in the combination of plowing with the Apica hybrid, where the maximum yield in the experiment was recorded at 3.27 t/ha, proving the economic and agrotechnical feasibility of individually selecting field tillage methods according to the biological potential of a specific soybean genotype.

The authors declared no conflict of interests.

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