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RESOURCE-EFFICIENT TECHNOLOGIES FOR CULTIVATION OF OILSEEDS, CEREALS AND LEGUMES IN CONDITIONS OF CLIMATE CHANGE AND INCREASE OF AGRICULTURAL PRODUCTION

S u m m a r y

Background. Sustainable soil management is a key factor in ensuring stable crop production under modern agricultural challenges. This study assessed the impact of primary tillage systems on the growth, productivity and quality of oilseed, cereal and legume crops under the conditions of climate change and intensified agricultural production. A three-year field experiment (2021 ÷ 2024) was conducted using a two-factor design with three replications, comparing four tillage systems – traditional, minimum, Strip-Till and No-till – across six crops. The study also evaluated the potential of these systems to reduce energy inputs and conserve soil moisture under variable climatic conditions.

Results and conclusions. Strip-Till and Minimum tillage created more favorable moisture and aeration conditions in the arable layer, enhancing vegetative growth and yield formation. Strip-Till increased plant height, leaf area and yield in winter wheat (5.82 t/ha) and winter rapeseed (3.46 t/ha). No-till proved to be the most effective for sunflower, maximizing leaf area and seed weight under arid conditions. Legumes responded best to Minimum tillage, with higher thousand-seed weight and yields in peas and chickpeas. Grain sorghum showed stable performance across all systems. Strip-Till and No-till also improved grain and oil quality. These technologies reduce fuel consumption and conserve soil moisture, ensuring stable productivity with lower energy inputs. Overall, adaptive tillage systems improve crop productivity and quality; Strip-Till is optimal for winter crops, No-till for sunflower, and Minimum tillage for legumes.

Keywords: winter wheat, winter rapeseed, sunflower, grain sorghum, chickpeas, peas, crop, quality, technologies, resource saving

Introduction

The climate changes observed between 1990 and 2020 pose significant challenges for agriculture, especially in the regions with risky farming practices. Increasing wea-

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ther instability, reduced rainfall during critical crop development phases, higher temperatures and soil degradation necessitate a fundamental review of the technologies used to grow major crops. In such conditions, the introduction of resource-saving technologies capable of reducing energy costs, conserving soil moisture and ensuring stable productivity is relevant. These technologies include adaptive tillage systems that can ensure the rational use of natural resources, reduce anthropogenic pressure and increase the efficiency of agricultural production. The growing intensification of agriculture requires a comprehensive approach to crop cultivation that incorporates not only the biological characteristics of plants, but also the agroecological constraints of the region. However, despite many studies, there is still insufficient comprehensive data in the scientific literature on the effectiveness of different primary tillage systems for a wide range of crops under current climate change conditions.

One of the pressing problems is the excessive intensity of traditional tillage, which leads to the destruction of soil structure, a decrease in organic matter content and water retention capacity. Shebanin et al. [45] studied the effects of regular ploughing on soil fertility. It was found that deep tillage causes degradation of agrophysical properties and reduces the water absorption coefficient. The scope of that research was restricted to only two crops and did not consider the effect under prolonged rainfall deficit.

An important direction in the ecologization of soil cultivation is the preservation and improvement of the physical properties of soil, which affects the formation of crop yields. Nikonchuk et al. [35] established the influence of surface tillage with tillage implements on the agrophysical properties of southern heavy loamy low-humus chernozem in the conditions of the Southern Steppe of Ukraine. Shebanin et al. [46] studied the Mzuri-ProTil technology, which demonstrates a significant increase in economic efficiency compared to traditional technologies for growing winter wheat. It provides higher yields, reduces the cost of production by optimizing costs and promotes adaptation to climate change.

The problem of soil moisture conservation in arid conditions has become a subject of research for many agronomists. Gamayunova et al. [17] studied the effect of Minimum tillage on the water regime of the arable layer in industrial crop cultivation systems. The results showed a decrease in moisture evaporation and an increase in its availability during critical growth phases. The experimental observations, however, covered only a limited period and did not allow the assessment of long-term dynamics.

Reducing energy costs while maintaining crop productivity became another line of research. Kachanova et al. [24] analyzed the energy efficiency of Strip-Till and No-till technologies in crop rotations with corn and soybeans. The study proved that these systems can reduce fuel consumption by $35 \div 45$ %. At the same time, yield performance under varying climatic conditions was not examined, which restricts broader interpretation of the results.

Drobitko et al. [10] studied the influence of different tillage methods on sunflower cultivation in the conditions of southern Ukraine. The studies found that the method of tillage significantly affects its density and water regime, as well as the growth and development of sunflower plants. It was proven that No-till technology contributed to an increase in moisture in the soil layer 0 ÷ 100 cm before harvesting sunflower by 25 mm compared to traditional tillage.

The formation of the leaf surface as a key factor in photosynthetic activity was examined in a study by Tetarwal et al. [48]. They demonstrated that different tillage systems have a significant impact on the morphometric parameters of plants. Particularly positive changes were observed when Strip-Till was used on rapeseed and wheat. The analysis, however, focused mainly on early growth stages and did not include final yield indicators. The adaptation of tillage systems to specific crop groups remains understudied. Walia et al. [51] addressed the specific response of leguminous crops to a reduction in the intensity of mechanical impact on the soil. The study determined that Minimum tillage promotes improved symbiotic nitrogen fixation. These findings were obtained only for chickpeas, while other legumes were not included in the experimental design. The adaptation of tillage systems to specific crop groups remains understudied, particularly in studies that simultaneously evaluate crop productivity, product quality and resource-use efficiency under current climate change conditions. Babu et al. [1] examined the effect of No-till on the protein and gluten content in wheat grain, demonstrating a significant increase in these indicators. However, the relationship between soil water regime and protein structure formation in different years of cultivation was not considered.

Oil crops react differently to agronomic conditions under climate change, which poses new challenges for researchers [42]. Rosegrant et al. [41] found that No-till increases the oil content in sunflowers, which is associated with a reduction in stress during budding. At the same time, crop structure and plant morphological parameters were not analyzed in that study. Yield stability under different agroclimatic conditions is a critical indicator of crop adaptability [49]. Nurbekov et al. [36] studied grain sorghum as an alternative crop under extreme conditions. It was proven that sorghum demonstrates stable yields under all types of cultivation. Nevertheless, the question of which technology provides the best product quality indicators remains unresolved.

Considering the above, there is an urgent need for a comprehensive analysis of the effectiveness of different tillage systems for a wide range of crops in the context of climate change and intensification of agricultural production. Therefore, the study aimed to assess tillage systems as adaptive and resource-efficient cultivation practices and their effects on the growth, productivity and quality of oilseed, cereal and legume crops under climate variability. The objectives of the study included an analysis of morphological changes in plants under different tillage technologies, an evaluation of soil moisture conservation and resource-use efficiency, an analysis of yield dynamics in relation to weather conditions, and an assessment of product quality characteristics depending on the tillage system.

Materials and methods

Field studies were conducted in 2021 ÷ 2024 in the Southern Steppe of Ukraine at the Educational, Scientific and Practical Center of Mykolaiv National Agrarian University. For winter crops, surveys were conducted during 2021 ÷ 2024, and for spring crops, in 2022 ÷ 2024. The soils of the experimental plots were classified as southern chornozems, residual-slightly saline, heavy loam on loess with a neutral soil solution reaction (pH 6.8 ÷ 7.2) and humus content in the 0 ÷ 30 cm layer at 3.1 ÷ 3.3 %. On average, 15-25 mg/kg of nitrate nitrogen (following the Grandval-Lazh method), 41 ÷ 46 mg/kg of mobile phosphorus (following the Machigin method) and 389 ÷ 425 mg/kg of exchangeable potassium (determined photometrically) were found in the arable layer. The soil profile showed consistent differentiation: humus-accumulative horizon (0 ÷ 30 cm), humus-transitional (30 ÷ 60 cm), humus-leaching horizon (60 ÷ 85 cm), transitional (85 ÷ 95 cm), carbonate (95 ÷ 140 cm) and loess parent material (below 140 cm).

According to data from the IMETOS weather station (Table 1), the meteorological conditions during the study period were typical for the southern region with a moderately arid climate. Average monthly temperatures ranged from -0.92 °C in January 2024 to 27.09 °C in July 2024. Air humidity remained predominantly high, which provided a certain buffer in the conditions of precipitation deficit during critical periods. The lowest precipitation levels were recorded in the summer months of 2022 and 2024, while in May and June 2023, significant precipitation was observed, which contributed to plant growth.

Table 1. Meteorological indicators (2021 ÷ 2024)

Date	Tcp [°C]	Tmax [°C]	Tmin [°C]	RHcp [%]	RHmax [%]	RHmin [%]	Precipitation [mm]
2024-12-01	1.99	10.14	-11.65	97.76	99.58	49.27	35.2
2024-11-01	2.91	18.15	-5.93	90.37	99.53	43.23	31.0
2024-10-01	11.72	26.24	0.37	89.21	99.64	31.81	62.4
2024-09-01	19.85	32.46	7.31	63.77	99.61	16.82	62.0
2024-08-01	24.30	38.80	11.87	57.19	99.58	13.13	23.0
2024-07-01	27.09	40.24	13.17	49.71	99.42	15.07	4.6
2024-06-01	22.85	35.02	11.10	68.80	99.58	20.92	82.8

2024-05-01	12.71	30.03	3.22	71.81	99.56	17.35	26.8
2024-04-01	11.60	26.49	-0.28	83.16	99.57	27.42	47.4
2024-03-01	2.98	23.37	-7.53	93.86	99.54	28.73	38.0
2024-02-01	2.83	12.17	-6.75	94.99	99.51	68.34	6.2
2024-01-01	-0.92	7.04	-14.39	99.17	99.48	92.53	38.0
2023-12-01	2.19	11.66	-3.86	97.44	99.52	70.31	23.2
2023-11-01	6.40	21.33	-10.43	94.76	99.48	32.33	116.8
2023-10-01	13.71	28.57	-1.63	74.98	99.48	23.03	10.2
2023-09-01	19.90	32.70	5.00	56.39	99.44	18.05	2.6
2023-08-01	24.71	39.95	11.64	65.22	99.44	17.48	36.2
2023-07-01	23.42	38.06	12.38	68.63	99.44	23.14	72.6
2023-06-01	20.88	34.44	5.23	65.99	99.41	19.10	19.2
2023-05-01	15.62	29.09	0.95	68.34	99.40	19.76	70.0
2023-04-01	10.06	21.24	0.49	88.64	99.40	33.46	95.6
2023-03-01	5.27	19.03	-6.06	84.17	99.41	30.83	32.4
2023-02-01	0.66	13.96	-11.64	84.46	99.39	30.34	10.6
2023-01-01	1.00	13.81	-10.11	93.54	99.38	53.59	3.0
2022-12-01	2.61	12.09	-9.25	96.49	99.37	74.24	57.2
2022-11-01	5.31	18.09	-3.29	94.37	99.36	31.54	40.2
2022-10-01	10.85	22.36	-0.14	77.49	99.35	25.64	15.2
2022-09-01	15.84	28.72	3.51	78.25	99.34	22.33	85.0
2022-08-01	24.35	37.30	14.86	67.50	99.33	15.34	43.2
2022-07-01	23.41	37.86	8.50	54.56	99.28	18.91	4.4
2022-06-01	21.69	35.76	9.60	62.79	99.32	18.63	24.8
2022-05-01	15.39	30.88	0.15	64.23	99.32	18.05	30.4
2022-04-01	9.62	24.69	-0.90	77.18	99.34	26.61	22.6
2022-03-01	1.77	21.47	-10.36	67.10	99.36	14.89	8.4
2022-02-01	2.41	13.40	-6.64	87.01	99.37	32.06	5.4
2022-01-01	-0.84	10.69	-15.31	90.09	99.36	37.15	21.0
2021-12-01	1.24	12.70	-15.38	96.35	99.40	65.06	51.4
2021-11-01	6.12	18.61	-6.56	91.94	99.48	40.58	39.2
2021-10-01	9.32	23.30	-1.57	69.00	99.24	27.20	48.4
2021-09-01	15.36	31.19	3.26	61.63	99.20	17.33	32.4
2021-08-01	23.27	35.33	11.42	60.48	99.23	22.02	19.0

Explanatory notes: the table shows the average, maximum and minimum values of air temperature (T), relative humidity (RH) and precipitation for each month from August 2021 to December 2024. The data are presented in the form of monthly averages obtained from daily observations.
Source: compiled by the authors based on IMETOS.

The experiment was designed according to a two-factor scheme with three replicates using the randomized block method. The area of one plot was 25 sq. m. Factor A – varieties and hybrids: linoleic-type sunflower hybrids (P64LE25, Sureli, ES Ceylon SU), oleic-type (Mas 86 OL, ES Emerik, P64GG150, LG50779 SKh, SI Flavio KLP);

winter rapeseed (Phoenix KL, KS Kalkulati KL, ES Imperio); winter wheat varieties (Duma Odessa, Perspektiva Odessa, Katrusya Odessa, Osnova Odessa); grain sorghum (Yankee, Bianca, U60116IG, U 60117 IG); peas (Darunok Stepu, Kruiz, Pristan); chickpeas (Skarb, Dostatok, Yarina). Factor B – four soil cultivation technologies. Four systems of basic soil cultivation were applied for factor Traditional technology included autumn ploughing to a depth of 25 ÷ 30 cm, surface levelling, pre-sowing cultivation, sowing based on agronomic terms and recommended plant density. In the Minimum tillage system, surface loosening of the soil without turning the layer to a depth of 10 ÷ 12 cm was applied using a Köckerling Trio (Germany) chisel cultivator, which reduced the agrotechnical load, preserved the structure of the top layer and minimized moisture loss. The limited number of passes by machinery and the preservation of plant residues on the surface ensured a reduction in erosion processes. Strip-Till technology was chosen for local soil cultivation and combined the advantages of minimal intervention and spot fertilization. For this purpose, an Orthman 1tRIPr (USA) unit was used, which formed treated strips 20 ÷ 25 cm wide and 15 ÷ 20 cm deep without disturbing the row spacing. This approach helped to improve the aeration of the root zone, accumulate moisture in the treated strip and reduce soil compaction. The No-till technology involved direct sowing into uncultivated soil with complete preservation of crop residues. The use of No-till was justified by the need to reduce energy costs, preserve soil structure, increase its biological activity and make effective use of residual moisture. The application of these three resource-saving systems made it possible to compare their effectiveness with the traditional ploughing model in terms of productivity, the stability of agrophysical parameters and crop quality indicators.

All technologies were applied to each variety and hybrid of all crops, incorporating their biological characteristics. Fertilization was conducted using the YaraMila Complex (Norway) mineral complex, which contains balanced forms of nitrogen, phosphorus and potassium, as well as sulfur and microelements, which determined its choice to ensure full mineral nutrition in the conditions of moisture deficiency. Application rates varied depending on the crop: for wheat, peas and chickpeas, N_{30}P60K60 kg/ha; for sunflower, rapeseed and sorghum, N_{60}P90K60 kg/ha. Pre-sowing seed treatment was conducted with the systemic fungicide Maxim XL 035 FS (Switzerland), which protected a complex of soil and seed pathogens in the early stages of growth. Biometric measurements were performed for 20 typical plants on each plot, which ensured statistical reliability. The height of the plants, the leaf area (determined by multiplying the length by the width of the leaves with a correction factor), the number of branches (for peas and chickpeas) or productive stems (for wheat and rapeseed), as well as the weight of 1,000 seeds following the DSTU 4138-2002 methodology [11]. Yield was determined by harvesting the entire recorded area, followed by recalculation to 100 % purity and standard moisture content (14 % for cereals and 8 % for oilseeds), following DSTU 7453:2013 [12]. The quality indicators of grain were assessed for wheat, rapeseed, sunflower, sorghum, peas and chickpeas. The crude oil content (for sunflower, rapeseed and sorghum) was determined following ISO 659:2009 [20]. The protein content was determined by infrared spectroscopy in accordance with ISO 20483:2013 [19], the nature of the grain by the DSTU GOST 10840:2019 [13], and gluten content (for wheat) – according to DSTU 4138-2002 [11]. All measurements were performed using an Infratec 1241 analyzer (Denmark), calibrated for each parameter in accordance with the specified standards. The data were statistically processed using Statistica 10.0 software (USA) with an analysis of variance (ANOVA) and the LSD criterion at a significance level of $p \leq 0.05$. Since the main objective of the study was to evaluate the effectiveness of soil cultivation systems for groups of crops (cereals, oilseeds, legumes), a statistical analysis was performed in the form of average values for varieties/hybrids of each crop. This negated excessive detail and identified general patterns of the impact of technologies.

Results

Biometric indicators of plants, in particular height, leaf area and the number of productive shoots/stems, varied significantly depending on the tillage system used and the type of crop. According to the results of observations in 2022 ÷ 2024, the highest average height indicators were observed in winter wheat and winter rapeseed under Strip-Till conditions, 103.2 cm and 118.5 cm, respectively, which exceeded the corresponding indicators under traditional tillage by 8.4 % and 6.7 %. In the No-till system, there was a slight decrease in height in most crops, but an increase in leaf area, especially in sunflowers (from 4,120 cm^2/plant in traditional technology to 4,525 cm^2/plant in No-till). Peas and chickpeas showed a stable number of productive shoots in all systems, but under Minimum tillage conditions, they had a higher vegetative mass, indicating better adaptation to moisture conservation. Sorghum showed the highest adaptability to No-till cultivation, maintaining the same height and density in all variants, demonstrating biological plasticity. Overall, Strip-Till and Minimum tillage promoted an optimal balance between vegetative growth and resistance to weather changes (Table 2).

The results of the field studies conducted between 2021 and 2024 demonstrated a significant impact of primary tillage systems on the biometric indicators of eight crops. An analysis of the data obtained shows that in the conditions of the Southern Steppe of Ukraine, the key factor in the adaptability of vegetative growth is the ability of the technology to ensure stable moisture content of the arable layer and optimal aeration. Among the technologies that most effectively met these requirements, Strip-Till and Minimum tillage stood out. Under these conditions, an improvement in growth parameters was observed in almost all crops, primarily due to an increase in leaf area and the number of productive shoots.

In winter wheat, Strip-Till provided the highest plant height gains (103.2 cm), which was 8.4 % higher than the same indicator for traditional technology. There was also an increase in the leaf area to 4,035 cm^2 per plant and an increase in the number of productive stems to 3.0, indicating overall optimization of vegetative growth. Winter rapeseed showed a similar response: Strip-Till stimulated intensive leaf formation (4,580 cm^2), and the number of branches increased to 5.8. Compared to traditional tillage, these indicators were 8.5 % and 13.7 % higher, respectively, indicating the

Table 2. Biometric indicators of major crops under different tillage systems (average values for 2022 ÷ 2024)

Crop	Cultivation system	Crop height [cm]	Leaf surface area [cm^2/plant]	Productive stems/ branches [pcs]
Winter wheat	Traditional	95.2	3.780	2.6
	Minimal	98.7	3.925	2.8
	Strip-Till	103.2	4.035	3.0
	No-till	94.3	4.090	2.7
Winter rapeseed	Traditional	111.0	4.220	5.1
	Minimal	115.3	4.430	5.6
	Strip-Till	118.5	4.580	5.8
	No-till	112.4	4.690	5.3
Sunflower	Traditional	165.3	4.120	1.0
	Minimal	169.5	4.380	1.0
	Strip-Till	171.0	4.450	1.0
	No-till	162.7	4.525	1.0
Grain sorghum	Traditional	142.5	3.620	2.1
	Minimal	141.7	3.760	2.2
	Strip-Till	143.0	3.795	2.2
	No-till	142.3	3.750	2.2
Peas	Traditional	66.2	2.920	4.1
	Minimal	68.0	3.035	4.3
	Strip-Till	67.5	3.050	4.3
	No-till	66.9	3.110	4.2
Chickpeas	Traditional	55.1	2.490	3.7
	Minimal	56.3	2.630	3.9
	Strip-Till	56.0	2.675	3.8
	No-till	55.6	2.750	3.8

Explanatory notes: data are presented as mean values ± standard deviation; the significance of differences was assessed using the LSD criterion at $p \leq 0.05$. Source: compiled by the authors.

positive effect of localized loosening and fertilizer application. Thus, strip tillage directed the energy of plant growth towards the formation of structural elements of productivity, avoiding excessive stress caused by full tillage.

In sunflowers, the No-till system demonstrated the most pronounced effect of increasing the assimilation surface (up to 4.525 cm^2/plant), which exceeded traditional technology by 9.8 %. Despite a slight decrease in height (up to 162.7 cm), the crop compensated for this with active growth of leaf mass, which efficiently accumulated photosynthetic energy. This confirms the hypothesis of the high ecological plasticity of sunflowers and their ability to adapt to surface technologies with complete preservation of plant residues [43]. It is worth noting that Strip-Till also showed positive results, but No-till proved to be more effective in terms of moisture conservation and mitigation of temperature stresses during the active growth stage.

Grain sorghum showed the least variability in performance between tillage systems. Its height remained stable at 142 ÷ 143 cm, regardless of the technology used. This confirms the high tolerance of this crop to agronomic factors and its effective realization of biological potential even with minimal impact on the soil. Peas and chickpeas, as legumes, are sensitive to water regime and respond better to Minimum tillage, showing increases in leaf area of up to 6.4 % in chickpeas and up to 3.8 % in peas compared to the traditional technology. At the same time, the number of productive branches remained stable or increased slightly, indicating the uniform development of vegetative and generative organs without the need for adaptation mechanisms under stressful conditions.

In general, traditional ploughing proved to be less effective in terms of the biometric parameters of most crops. Although in some cases (especially in the years with excessive rainfall) its use did not cause growth inhibition, in the conditions of moisture deficiency, it often contributed to a decrease in vegetative mass due to the disruption of capillary water rise, surface overheating and mechanical soil compaction after intensive tillage. Thus, the results demonstrate the advantages of Strip-Till and Minimum tillage as universal systems capable of ensuring stable plant development in a wide range of weather scenarios typical of the southern steppe of Ukraine [3, 5].

In addition to biometric growth indicators, the response of crops to tillage systems was also reflected in seed formation parameters, particularly the weight of 1,000 seeds. This indicator also varied significantly depending on the tillage system and crop used. In general, better results were observed under Strip-Till conditions, which ensured a uniform supply of nutrients and moisture retention in the active root formation zone. In winter wheat, the weight of 1,000 seeds increased from 39.8 g in traditional technology to 42.3 g in Strip-Till. In sunflowers, the indicator reached its maximum in No-till (67.9 g), which exceeded the ploughing option by 5.4 %. Legumes such as peas and chickpeas responded best to Minimum tillage, where they formed denser and more massive seeds. The smallest fluctuations in weight were found in sorghum, which remained stable regardless of the technology used. The results demonstrate the importance of combining the biological characteristics of a crop with adaptive agricultural techniques (Table 3). These patterns generally correspond to the differences observed in biometric indicators presented in Table 2. Overall, Strip-Till was most effective for winter crops (winter wheat and rapeseed), No-till for sunflower, while Minimum tillage provided the best results for legumes.

Table 3. Weight of 1,000 seeds depending on the soil cultivation system (average for 2022 ÷ 2024)

Crop	Traditional	Minimal	Strip-Till	No-till
Winter wheat	39.8 g	41.2 g	42.3 g	40.7 g
Winter rapeseed	4.63 g	4.89 g	5.01 g	4.92 g
Sunflower	63.4 g	65.6 g	66.8 g	67.9 g
Grain sorghum	28.7 g	29.0 g	29.2 g	28.9 g
Peas	194.1 g	198.5 g	196.8 g	195.4 g
Chickpeas	218.3 g	224.7 g	222.9 g	220.5 g

Explanatory notes: data are presented as mean values ± standard deviation; the significance of differences was assessed using the LSD criterion at $p \leq 0.05$. Source: compiled by the authors.

Further analysis confirms that the effect of tillage systems on seed weight differs between crop groups. The most pronounced positive response to the change in agricultural technology was demonstrated by winter wheat, winter rapeseed and sunflower, which, under Strip-Till and No-till conditions, formed seeds with a higher weight than under traditional tillage. In winter wheat, which is sensitive to temperature and moisture conditions during the grain filling phase, Strip-Till provided the highest weight of 1,000 seeds at 42.3 g, which is 6.3 % more than the traditional technology (39.8 g). This is due to improved moisture supply during the critical period and better root system development, thanks to deeper loosening of the strips without continuous cultivation. In winter rapeseed, Strip-Till also proved to be the most effective: the weight of 1,000 seeds reached 5.01 g, which was 8.2 % higher than the control (4.63 g). The explanation for this lies in moisture conservation and reduced temperature stress during pod formation. In addition, localized fertilizer application in strips promoted better nutrient transport to the generative organs, ensuring more complete seed formation. Minimum tillage showed slightly lower results, but also exceeded the traditional technology, confirming the general trend towards increased weight with less intensive mechanical intervention in the soil.

In sunflowers, the highest seed weight was recorded with No-till – 67.9 g, which is 5.4 % more than with traditional tillage (65.6 g). This result is due to the exceptional adaptability of the crop to surface cultivation and the preservation of plant residues, which act as mulch, reduce evaporation and stabilize the microclimate during the seed filling phase. In addition, a reduction in soil temperature during the critical period promotes better nutrient uptake [34]. It should be noted that the difference between No-till and Strip-Till was insignificant (67.9 vs. 66.8 g), but in favor of the former, which therefore can be considered a viable alternative in the conditions of increased aridity. Grain sorghum showed high stability, with the weight of 1,000 seeds ranging from 28.7 to 29.2 g, regardless of the cultivation technology. This indicates the biological resistance of the crop to agrotechnical variations, due to its ability to form a deep root system and effectively use available moisture and nutrient resources, even with reduced mechanical intervention in the soil.

Legumes such as peas and chickpeas showed the maximum response to Minimum tillage. In peas, the weight of 1,000 seeds increased from 194.1 g to 198.5 g, and in chickpeas, from 218.3 g to 224.7 g, which corresponded to increases of 2.3 % and 2.9 %, respectively. These crops have a short growing season and high moisture demand during seed formation, hence water conservation in the topsoil is critical to their reproductive efficiency. Minimum tillage reduced water loss through evaporation and preserved microflora, which had a positive effect on symbiosis with nodule bacteria and the formation of full-fledged seeds. In general, all resource-saving technologies demonstrated an advantage over the traditional system in terms of seed mass formation. Strip-Till provided the highest biological efficiency for winter crops, No-till for sunflowers, while Minimum tillage was most beneficial for legumes. This highlights the need for an adaptive approach to the choice of a tillage system depending on the type of crop, its physiological and biochemical needs, and the weather conditions of the year [4].

Crop yields depended largely on the tillage system used, which was particularly evident during the contrasting weather conditions of 2022 ÷ 2024. On average, over three years, the highest yields of winter wheat and winter rapeseed were recorded using Strip-Till technology, which provided favorable conditions for initial growth and effective fertilizer uptake. Wheat reached 5.82 t/ha and rapeseed 3.46 t/ha. Sunflower, due to its high adaptation to arid conditions, realized, to the greatest extent, its potential with No-till technology (2.73 t/ha). Sorghum, peas and chickpeas showed high stability, but had an advantage with Minimum tillage, where the best combination of moisture conservation and microbiological activity was observed. Thus, the optimal technology is crop-specific and must address the physiological needs of plants (Table 4).

An analysis of the yield results for major crops in the 2022 ÷ 2024 study revealed systemic patterns between the type of tillage technology and plant productivity. The highest yield indicators were recorded for winter cereals and oilseeds when using Strip-Till: 5.82 t/ha for winter wheat and 3.46 t/ha for winter rapeseed. It is worth noting that this increase in yield was also accompanied by an improvement in crop structure, with more uniform plant density, a reduction in the number of uneven ears or pods, and a higher percentage of full-bodied grains. The effectiveness of Strip-Till is determined by the fact that this technology provides deep loosening of the soil within the sowing strip, while keeping the inter-rows untouched, which contributes to optimal water balance and precise fertilizer application. In combination with suitable varieties with a potent root system, this technology maximizes the genetic potential of the crop in conditions of limited rainfall [21].

Table 4. Yield of major crops by tillage systems (t/ha, average for 2022 ÷ 2024)

Crop	Traditional	Minimal	Strip-Till	No-till
Winter wheat	5.12	5.44	5.82	5.27
Winter rapeseed	2.94	3.21	3.46	3.12
Sunflower	2.29	2.51	2.64	2.73
Grain sorghum	3.82	4.08	4.13	4.06
Peas	2.11	2.28	2.22	2.17
Chickpeas	1.87	2.04	2.01	1.95

Explanatory notes: data are presented as mean values ± standard deviation; the significance of differences was assessed using the LSD criterion at $p \leq 0.05$. Source: compiled by the authors.

Winter wheat, in particular, was sensitive to initial growing conditions. In the traditional ploughing variants, uneven germination was observed after rainfall due to compaction of the sowing horizon, while in No-till, rooting was slowed down due to the cool microclimate. In contrast, Strip-Till managed to combine aeration, heat and moisture in the root zone. This promoted synchronous tillering, resulting in a high number of productive stems and grains in the ear. A similar pattern was observed in winter rapeseed, which, due to its long taproot, penetrates deeper into the soil in the presence of local loosening and moisture. The advantage of Strip-Till in this crop was particularly evident in 2023, when the spring moisture deficit limited development in the traditional technology variants.

Sunflower yield was highest in the No-till system at 2.73 t/ha, which is 18 % higher than traditional ploughing. This indicates the crop's high adaptability to the conditions of crop residue retention and surface tillage. On average, the difference between Strip-Till and No-till in this crop was only 3.1 %, but the latter provided more stable results in the years with low rainfall. The preservation of plant residues on the surface significantly influenced the reduction of soil temperature and evaporation, which is critical in the seed filling phase. At the same time, the early development of sunflowers in No-till was slower, but the plants compensated for this later with intensive growth of baskets and seed mass. Legumes, peas and chickpeas showed a clear preference for Minimum tillage. Peas reached a maximum yield of 2.28 t/ha, chickpeas – 2.04 t/ha, which is 8.1 % and 9.1 % higher than the control, respectively. Minimum tillage ensured the preservation of soil structure, biological activity of microflora and better development of nodule bacteria. Compared to No-till, where the soil temperature in spring was lower, Minimum tillage promoted a faster start for legumes, which is substantial for crops with a short growing season.

Grain sorghum, as a crop with a high level of drought resistance, showed insignificant fluctuations in yield between technologies. However, the maximum value was achieved with Strip-Till (4.13 t/ha), indicating a synergistic effect between local tillage and deep root system placement. Overall, sorghum showed the least dependence on the technological factor, confirming its suitability for extreme farming conditions. Thus, the results of the study prove that the introduction of adaptive tillage systems provides a significant increase in yield by optimizing growing conditions following the biological needs of the crop. Strip-till and No-till technologies demonstrate the highest efficiency with the right selection of crops and varieties, while traditional tillage is inferior in conditions of limited moisture and increasing climatic risks.

Table 5. Quality indicators of products by soil cultivation systems (average for 2022 ÷ 2024)

Crop	System	Protein [%]	Crude fat/oil [%]	Gluten [%]	Natural [g/l]
Winter wheat	Traditional	12.6	–	21.8	765
	Minimal	13.2	–	23.5	777
	Strip-Till	13.9	–	24.1	789
	No-till	13.0	–	22.8	775
Winter rapeseed	Traditional	20.4	44.9	–	–
	Minimal	21.2	46.3	–	–
	Strip-Till	21.7	47.1	–	–
	No-till	21.0	47.6	–	–
Sunflower	Traditional	–	49.5	–	–
	Minimal	–	50.6	–	–
	Strip-Till	–	50.9	–	–
	No-till	–	51.2	–	–
Grain sorghum	All systems	10.8	–	–	713-717
Peas	Traditional	21.5	–	–	755
	Minimal	22.0	–	–	764
Chickpeas	Traditional	23.1	–	–	738
	Minimal	23.4	–	–	746

Explanatory notes: data are presented as mean values ± standard deviation; the significance of differences was assessed using the LSD criterion at $p \leq 0.05$. Source: compiled by the authors.

An analysis of product quality characteristics revealed significant differences between crops and tillage systems. The highest protein content in winter wheat grain was recorded with Strip-Till – 13.9 %, which exceeded traditional technology by 1.3 percentage points. Gluten content was also the highest in this system. For rapeseed and sunflower, the crude oil content was maximized with No-till, reaching 47.6 % and 51.2 %, respectively, indicating effective moisture retention during the filling period. In legumes, protein levels remained stable regardless of the system, but Minimum tillage contributed to a slight increase in grain quality. Sorghum demonstrated the greatest stability in all parameters. Overall, Strip-Till and No-till provided the highest grain quality when optimally combined with varietal characteristics (Table 5).

To provide a clearer interpretation of the results, an integrated evaluation of tillage system efficiency combining yield, seed weight, product quality indicators and resource-saving effects was conducted (Table 6).

Table 6. Integrated evaluation of the efficiency of tillage systems for major crops

Crop	Highest yield	Best seed weight	Best quality indicators	Resource-saving effect	Most efficient system
Winter wheat	Strip-Till	Strip-Till	Strip-Till	High moisture conservation	Strip-Till
Winter rapeseed	Strip-Till	Strip-Till	Strip-Till / No-till	Improved soil moisture retention	Strip-Till
Sunflower	No-till	No-till	No-till	High residue retention	No-till
Grain sorghum	Strip-Till / Minimal	Relatively stable	Relatively stable	Moderate resource-saving effect	Strip-Till / Minimal
Peas	Minimal	Minimal	Minimal	Improved moisture conservation	Minimal
Chickpeas	Minimal	Minimal	Minimal	Improved moisture conservation	Minimal

Explanatory notes: compiled by the authors.

The integrated assessment confirms that Strip-Till is generally most effective for winter crops, No-till for sunflower, while Minimum tillage provides the best results for legumes.

The quality characteristics of grain and seeds formed under different primary tillage systems showed significant dependence on the type of crop and agrotechnological scheme. The analysis showed that high-quality indicators of winter cereals and oilseeds, in particular winter wheat and rapeseed, were best formed in the variants with strip-till and No-till cultivation. In winter wheat, the protein content increased from 12.6 % with traditional technology to 13.9 % with Strip-Till. At the same time, the proportion of raw gluten increased from 21.8 % to 24.1 %, indicating favorable nitrogen nutrition conditions during critical phases of generative development. The increase in grain weight to 789 g/l with Strip-Till also indicates better grain filling due to moisture retention in the arable layer, reduced temperature stress and a stable supply of nutrients. Minimal tillage provided a moderate improvement in quality, while traditional technology showed a decrease in protein potential, probably due to excessive humus oxidation and losses of available nitrogen. In winter rapeseed, the highest crude oil content (47.6 %) was observed with No-till, indicating the effectiveness of moisture retention during seed formation. At the same time, Strip-Till provided a close value of 47.1 %, but with a better combination of protein fraction (21.7 %), which makes this technology promising in terms of comprehensive quality assessment. Under traditional cultivation conditions, rapeseed produced fewer viable seeds due to the topsoil desiccation during the filling phase, which had a negative impact on oil content.

Sunflower demonstrated the best results in the No-till system, with 51.2 % crude oil content, which exceeded traditional cultivation by 1.7 percentage points. This is explained by the stable microclimate in the sowing horizon, a reduction in the temperature load on the generative organs, and a decrease in water stress. Strip-till and Minimum tillage technologies also provided high oil content, indicating the adaptive potential of sunflowers to resource-saving systems. Legumes, peas and chickpeas showed sensitivity to the hydrothermal regime during the seed filling period. With Minimum tillage, the protein content increased to 22.0 % in peas and 23.4 % in chickpeas, which is a typical response to improved soil water balance. In addition, under the conditions of less mechanical impact on the soil, the structure of the rhizosphere was preserved, which contributed to the activity of nodule bacteria. The increase in grain weight in legumes with Minimal tillage (up to 764 g/l in peas and 746 g/l in chickpeas) indicates better seed filling and the absence of empty seeds. No-till in these crops showed moderate results, probably due to a delay in soil warming in the early stages of growth, which is important for heat-loving crops with a short growing cycle.

In contrast to other crops, grain sorghum demonstrated a high degree of stability in quality indicators across all agricultural technologies. The protein content remained at 10.8 %, and the grain weight fluctuated between 713 and 717 g/l, with no statistically significant differences. This confirms that sorghum is a strategically important crop for the extreme conditions of the Southern Steppe, capable of producing stable quality even when using No-till farming. In summary, it is possible to argue that Strip-Till was the most effective for producing high-quality grain in wheat and rapeseed, No-till for sunflowers, and Minimum tillage for legumes. Traditional ploughing was inferior in all key parameters, which emphasizes the advisability of transitioning to adaptive, resource-saving agriculture, considering the species-specific requirements of crops.

Discussion

This study revealed a significant impact of tillage systems on the biometric, morphometric, productive and qualitative indicators of major field crops. The results of the analysis indicate the need to adapt agrotechnical approaches to the physiological and biochemical characteristics of crops, as well as the effectiveness of Strip-Till and Minimum tillage as tools for moisture conservation, microclimate stabilization and improved plant nutrition in the climatically vulnerable conditions of the Southern Steppe. This effect can be explained by improved soil moisture retention and reduced evaporation losses under reduced soil disturbance, which contributes to more stable temperature conditions in the root zone and enhances plant physiological activity during critical growth stages.

In particular, the observed increase in the height of winter wheat and winter rapeseed in the Strip-Till system indicates its favorable effect on the initial stages of growth. Similar results were obtained by Visha Kumari et al. [50], recording improved growth characteristics of winter crops in the strip system, due to spot loosening and local fertilizer application. In turn, Jensen et al. [23] noted the advantage of Strip-Till for crops with deep root systems, in particular rapeseed, under conditions of moisture deficiency. Thus, a comparative analysis confirms the effectiveness of Strip-Till in increasing the adaptive potential of winter crops. The strip-based soil loosening creates favorable conditions for root penetration and improves water and nutrient availability in the rhizosphere, which supports more efficient physiological responses of crops under the conditions of limited soil moisture [52]. Data on the leaf area of sunflower under No-till conditions are consistent with the conclusions of Rodriguez et al. [40], highlighting the high ecological plasticity of this crop to surface technologies. Dowling et al. [8] emphasized that an increase in leaf area does not always correlate with an increase in yield. In the present study, sunflower productivity indicators also improved under No-till conditions, confirming the effectiveness of this technology for crops adapted to reduced soil disturbance, especially in arid climates. The preservation of surface residues under No-till additionally reduces soil temperature fluctuations and evaporation, creating a more stable hydrothermal regime for crop development [15].

Regarding the biological stability of sorghum, the results correlate with the data of Dowling et al. [9], highlighting the low sensitivity of this crop to variations in cultivation. Dutta et al. [14], however, questioned the ability of sorghum to maintain yield under prolonged No-till application, arguing that this was due to possible degradation of the topsoil. Nevertheless, the data from the current study show that sorghum, due to its physiological characteristics, including its well-developed root architecture, demonstrates high tolerance to reduced mechanical impact on the soil. This physiological characteristic enables efficient water uptake from deeper soil horizons, which is particularly advantageous under precipitation deficit. The observed stability of biometric and productive parameters across tillage systems further confirms the crop's ecological plasticity and suitability for cultivation in climate-risk regions. The absence of statistically significant differences between the variants indicates the effective realization of the genetic potential of sorghum even under stressful conditions, making this crop strategically relevant for areas of high-risk agriculture.

Legumes such as peas and chickpeas demonstrated the best morphometric indicators under Minimum tillage conditions [16]. This fact confirms the results of Księżak et al. [29], establishing a close relationship between soil biological activity and legume productivity. At the same time, Jaidka and Brar [22] indicated the advantages of No-till for preserving microbiota. The present results suggest that Minimum tillage may provide a better balance between soil biological activity and early-season soil warming, which is important for the successful development of legumes in regions with relatively short growing seasons.

The assessment of the weight of 1,000 seeds confirmed the importance of Strip-Till technology for cereals and rapeseed. In particular, winter wheat showed the highest weight with strip tillage, which is consistent with the conclusions of Khatun et al. [28] regarding the significance of water supply during the grain filling phase. In rapeseed, a similar effect was described by Mirdoraghi et al. [32], correlating the improvement in generative parameters with the local placement of fertilizers and the minimization of moisture loss. Thus, Strip-Till confirms its advantage in terms of producing high-quality seed material [26]. Sunflower, on the other hand, showed the highest seed weight with No-till. Cattani [7] also reported a positive effect of surface tillage on the generative characteristics of this crop. However, Yong and Wu [53] noted that No-till technology requires careful weed management. In the present experiment, no negative impact of weed infestation was observed, which can be attributed to the use of inter-row mulching, which enhances the effectiveness of the technology.

In the case of legumes, an increase in the weight of 1,000 seeds with Minimal tillage correlates with the data of Kagale and Close [25], highlighting the role of microflora in symbiotic nitrogen fixation. The effective activity of nodule bacteria in a less disturbed soil environment contributes to the intensification of nitrogen nutrition, which directly affects the quality of the formed seeds. Furthermore, reduced soil disturbance helps preserve rhizosphere structure, creating favorable conditions for the functioning of symbiotic complexes. At the same time, Reckling et al. [39] denied the advantages of Minimum tillage, highlighting the uneven formation of crops, especially in the cases of insufficient mechanical levelling of the surface. In contrast, the results of the present study indicate that uniform crop development can be maintained under Minimum tillage, provided there is sufficient moisture saturation, careful crop rotation planning and high-quality seedbed preparation. Thus, Minimum tillage can be considered an effective alternative for leguminous crops in adaptive farming systems, combining economic feasibility with environmental sustainability [27].

The yield of winter crops was the highest with Strip-Till. This correlates with the conclusions of Oller et al. [38], highlighting the importance of initial loosening for tillering and ear formation. Mkhize et al. [33], however, did not confirm the advantages of Strip-Till in the context of long-term use, citing the possible accumulation of pathogens in the strips. Such effects were not observed in the present study, which may be explained by the implementation of crop rotation and balanced agronomic management.

According to the results, sunflowers performed better with No-till, which is consistent with the data of Maraveas et al. [31]. Reduced evaporation and stabilized temperatures created favorable conditions during the seed filling period. Kumari et al. [30] expressed doubts about the feasibility of No-till in the regions with excessive soil density. However, in the conditions of the Southern Steppe, where light mechanical composition prevails, no such limitations were found. Minimum tillage provided the best yield indicators in leguminous crops, which is consistent with the conclusions of Sher et al. [47]. In particular, their study indicated an increase in nodule bacteria activity with reduced mechanical intervention. Ojiewo et al. [37], on the other hand, believed that deep loosening was necessary for the formation of a full chickpea yield. Corresponding observations in 2022 ÷ 2024 did not confirm this hypothesis: Minimum tillage proved to be optimal for legumes due to improved soil structure and hydrothermal regime.

An analysis of grain quality indicators showed that Strip-Till promotes an increase in protein and gluten content in wheat, which corresponds to the results of Bousselin et al. [2]. The increase in protein content indicates effective nitrogen assimilation during critical phases of plant development, particularly during the milk ripeness phase, when the need for nutrients is the highest. Cai et al. [6] also noted an improvement in grain quality due to reduced temperature stress during the filling phase. This suggests that Strip-Till creates a more stable microclimate in the seedbed, promoting the accumulation of plastic substances in the grain. In addition, uniform loosening and spot application of fertilizers ensured better root system development, which increased the transport of nutrients during grain formation [18, 44]. This is confirmed by the results of the current study, indicating improved nitrogen assimilation and more favorable conditions for grain filling.

In general, this study confirms the effectiveness of adaptive tillage systems such as Strip-Till, Minimum tillage and No-till in ensuring stable growth, high yields and high-quality grain characteristics. Different systems have specific advantages depending on the crop: Strip-Till for cereals and rapeseed, No-till for sunflowers and Minimum tillage for legumes. The conditions of the Southern Steppe of Ukraine, with its characteristic aridity and high variability of weather factors, determine the need for a flexible approach to the choice of technologies based on crop properties, soil types and meteorological forecasting. This approach can efficiently combine agrotechnical innovations with the principles of sustainable farming.

Conclusions

1. A comprehensive analysis of field data for 2021 ÷ 2024 reliably assessed the impact of primary tillage systems on the growth, development, productivity and quality of crops in the agroecological conditions of the Southern Steppe of Ukraine. The results confirmed that adaptive technologies such as Strip-Till, No-till and Minimum tillage outperform traditional ploughing in most key biometric, morphometric and agronomic parameters. Strip-Till provided the highest plant height (up to 118.5 cm in winter rapeseed), leaf area (up to 4,580 cm^2/plant) and the maximum possible number of productive stems/branches. These data indicate better initial growth dynamics and increased efficiency of moisture and nutrient use during critical phases of organogenesis. In winter wheat, Strip-Till provided an increase in height by 8.4 %, leaf area by 6.8 % and the number of stems by up to 3.0 per plant, which correlated with an increase in yield to 5.82 t/ha.
2. No-till, in turn, proved to be the most effective for crops with high plasticity to arid conditions, in particular sunflowers. Under the conditions of complete preservation of plant residues and minimal mechanical intervention, there was an increase in the assimilation surface (+9.8 %) and the weight of 1,000 seeds (up to 67.9 g), which ensured the highest yield (2.73 t/ha). The advantages of No-till were also evident in product quality: the raw oil content in sunflowers reached 51.2 %. Minimal tillage demonstrated the greatest effectiveness in legumes (peas, chickpeas), which are sensitive to water regime and soil structure. This system increased the weight of 1,000 seeds (peas to 198.5 g; chickpeas to 224.7 g) and improved quality indicators (protein content, natural weight), which led to an increase in yield to 2.28 and 2.04 t/ha, respectively. The stability of the morphometric and quality parameters of grain sorghum regardless of the technology (weight of 1,000 seeds: 28.7 ÷ 29.2 g; yield: 3.82 ÷ 4.13 t/ha) confirms its high biological tolerance and suitability for extreme farming conditions typical of arid steppe agroecosystems.
3. This study has several limitations. The experiment was conducted within a single agro-climatic region (the Southern Steppe of Ukraine) and covered a three-year observation period, which may not fully capture long-term soil processes or variability across other climatic zones. Further research should address the long-term monitoring of the impact of adaptive tillage systems on soil biological activity, carbon balance, economic viability and the resilience of agroecosystems to climatic stresses in different agroecological regions.

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TECHNOLOGIE WYDAJNOŚCIOWE W UPRAWIE ROŚLIN OLEISTYCH, ZBÓŻ I ROŚLIN STRĄCZKOWYCH W WARUNKACH ZMIAN KLIMATU I WZROSTU PRODUKCJI ROLNICZEJ

S t r e s z c z e n i e

Wprowadzenie. Zrównoważone zarządzanie glebą stanowi kluczowy czynnik gwarantujący stabilną produkcję roślinną w obliczu wyzwań współczesnego rolnictwa. W niniejszym badaniu oceniono wpływ systemów uprawy pierwotnej na wzrost, plonowanie i jakość roślin oleistych, zbóż i roślin strączkowych w warunkach zmian klimatu i intensyfikacji produkcji rolnej. Trzyletnie doświadczenie polowe (2021 ÷ 2024) przeprowadzono w układzie dwuczynnikowym z trzema powtórzeniami, porównując cztery technologie uprawy roli – tradycyjną, minimalną, pasową i bezorkową – w sześciu uprawach. W badaniu oceniono również potencjał tych systemów w zakresie ograniczenia nakładów energetycznych oraz zachowania wilgotności gleby w warunkach zmiennej zmienności klimatycznej.

Wyniki i wnioski. Uprawa pasowa i minimalna stworzyły korzystniejsze warunki wilgotności i napowietrzenia w warstwie ornej, poprawiając wzrost roślin i plonowanie. Uprawa pasowa (strip-till) zwiększyła wysokość roślin, powierzchnię liści i plon pszenicy ozimej (5,82 t/ha) i rzepaku ozimego (3,46 t/ha). Uprawa bezorkowa okazała się najskuteczniejsza w przypadku słonecznika, maksymalizując powierzchnię liści i masę nasion w warunkach suchych. Rośliny strączkowe najlepiej reagowały na uprawę minimalną, osiągając wyższą masę tysiąca nasion i plony grochu i ciecierzycy. Sorgo ziarniste wykazało stabilną wydajność we wszystkich systemach. Uprawa pasowa i bezorkowa również poprawiły jakość ziarna i oleju. Technologie te zmniejszają zużycie paliwa oraz sprzyjają zachowaniu wilgotności gleby, zapewniając stabilną produkcję przy niższych nakładach energetycznych. Ogólnie rzecz biorąc, adaptacyjne systemy uprawy znacznie poprawiają wydajność i jakość upraw; uprawa pasowa jest optymalna dla upraw ozimych, uprawa bezorkowa dla słonecznika, a uprawa minimalna dla roślin strączkowych.

Słowa kluczowe: pszenica ozima, rzepak ozimy, słonecznik, sorgo ziarniste, ciecierzyca, groch, plon, jakość, technologie, ochrona zasobów