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Productivity of winter wheat under cultivation technologies of different intensity

Olena DEMYANYUK[1], Kateryna OLIINYK[2], Hanna DAVYDIUK[2], Volodimir YULA[2], Kateryna SHATKOVSKA[3], Ivan MOSTOVIAK[4]

[1]National Academy of Agrarian Sciences of Ukraine,
Institute of Agroecology and Environmental Management
12 Metrologichna St., 03143 Kyiv, Ukraine

[2]National Scientific Centre Institute of Agriculture
of the National Academy of Agrarian Sciences of Ukraine
2-B Mashynobudivnykiv St., Chabany vil., 08162 Kyiv reg., Ukraine

[3]Lithuanian Research Centre for Agriculture and Forestry, Institute of Agriculture
Instituto Ave. 1, Akademija, 58344 Kėdainiai dist., Lithuania
E-mail: kateryna.shatkovska@lammc.lt

[4]Uman National University of Horticulture
1 Instytutska St., 20305 Uman, Ukraine

Abstract

One of the main directions of agricultural production in Ukraine is the stabilisation and increase in the production of high-quality food grains, which will ensure the country's food security and increase the export potential. Increasing the yield of winter wheat (*Triticum aestivum* L.), the main grain crop of the country, is important in this regard. The purpose of the study was to investigate the influence of different intensity cultivation technologies on the productivity of winter wheat. The experiment was carried out in 2016–2020 and based on a stationary multifactorial experiment of the Department of Technology of Grain and Ear Crops of the National Scientific Centre Institute of Agriculture of the National Academy of Agrarian Sciences of Ukraine. Models of cultivation technologies were studied, which differed in the rates of applied mineral fertilisers, the insertion of pea straw residues, and the application of the plant protection system (PPS). The results showed a positive effect of the cultivation technologies with increasing intensity on the formation of winter wheat productivity. The amount of vegetative mass, the level of accumulation of the dry matter of plants, the density of productive stems, the length of the ear, the number of spikelets per ear, and the grain size of the ear increased. The factor 'fertilisation system' had the greatest influence (79.3%) on the formation of winter wheat grain yield. The highest grain yield was obtained by the highly intensive 1 (HI1) cultivation technology, which provided for the application of $P_{80}K_{100}N_{240}$ fertilisers with the background of the straw residues of preceding crop and integrated PPS, which was 8.93 t ha^{-1} (excess to control was 4.71) with the best indicators of grains quality, protein content of 13.3–13.8%, and gluten content of 23.3–24.6%. On application of the studied technologies, winter wheat did not significantly accumulate copper, zinc, manganese, and iron.

Keywords: winter wheat, cultivation technologies, *Triticum aestivum*, fertiliser rate, grain quality, grain yield.

Introduction

Winter wheat (*Triticum aestivum* L.) is an important food crop, which occupies the largest specific weight in the structure of cultivated areas of Ukraine – about 24%. According to the data of the State Statistics Service of Ukraine (https://ukrstat.gov.ua/), the harvested area of winter wheat in 2021 was 6.9 million hectares, and the volume of grain production was 31.37 million tons. At the same time, the total export of winter wheat grains was 20.4 million tons.

European countries, primarily the countries of the European Union, are important trading partners of Ukraine. The wheat grain from Ukraine is in demand in European countries with an arid climate (Italy and Spain), the lack of agricultural land (Netherlands and Ireland),

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and a low natural soil fertility (Germany) (Budziak, Budziak, 2020).

Russia's military actions in Ukraine in 2022 led to a decrease in winter wheat harvesting areas and a reduction in grain production and sowing areas for the 2023 harvest. Due to the blocked seaports, the volume of grain export has significantly decreased, which makes the issue of food security particularly relevant. This has negative social and economic consequences at the international level, which can cause a deterioration in global food security and limit the use of production resources (Hassen, Bilali, 2022). Realisation of the genetic potential of winter wheat under limited resources (insufficient amount of fertilisers, pesticides, etc.) in modern conditions requires the development and improvement of resource-saving wheat cultivation technologies. In July 2020, Ukraine supported the European Green Course at the political level and recognised that it is an integral part of the realisation of its goals.

In agriculture, an increase in the share of organic production and requirements for agricultural technologies is expected (Ivanyuta, Yakushenko, 2022). The European Union recommends the balanced use of mineral fertilisers and plant protection products in agricultural production (integrated production) or the use of only natural production methods (organic production) (Mitura et al., 2023).

Considerable attention is paid to the application of various winter wheat cultivation technologies in Europe. High efficiency of resource use is one of the main goals to produce high-quality winter wheat grains. Fertiliser application, plant protection, and the effect of preceding crops can alter system performance in terms of winter wheat grain yield, quality, and environmental performance (Mayer et al., 2015). In modern conditions, agricultural producers seek to obtain a high yield of high-quality grains reducing the cost of production and using environmentally safe technologies (Litke et al., 2018). Increasing the grain yield of winter wheat increases its production, but at the same time possesses many risks for both the environment and the health of consumers (Sułek, Cacak-Pietrzak, 2018).

Organic production usually results in significantly lower costs, higher labour requirements, lower yields, and higher prices compared to the conventional system. In addition, organic production provides environmental benefits that are often difficult to monetise (Durham, Mizik, 2021). Also, a natural factor – the global warming of the climate – has a great influence on the change in approaches of winter wheat cultivation (Wang et al., 2018; Ray et al., 2019; Zhang et al., 2022). In modern climate change and prevailing socio-economic conditions, a new approach is needed to the development of technologies for cultivation of high-quality winter wheat grains. To reduce the negative impact of climate change on agricultural crops including winter wheat, it is necessary to adapt cultivation technologies to constantly changing environmental factors. Such technologies which can ensure a high productivity and grain quality are developed taking into account the biological characteristics of the crop, its response to environmental changes, especially during critical periods of growth and development, and a complex of factors affecting the plant growth and development. Therefore, relevant research is aimed at studying the formation of winter wheat productivity by applying cultivation technologies of various intensities.

The purpose of this experiment was to investigate the influence of different intensity cultivation technologies on the formation of the productivity of winter wheat and its individual elements to obtain high yield of high-quality grain.

Material and methods

The experiment was carried out based on a stationary multifactorial experiment of the Department of Technology of Grain and Ear Crops of the National Scientific Centre Institute of Agriculture of the National Academy of Agrarian Sciences (NSC IA NAAS) of Ukraine in the state enterprise Experimental Farm of Chabany, Fastiv District, Kyiv Region, the northern part of the right-bank Forest-Steppe of Ukraine in 2016–2020. The soil of the experimental site is *Luvic Phaeozem* (WRB, 2022) in the plough horizon with a texture of loam consisting of 31.5% clay, 51.5% silt, and 17.0% sand, with a low content of humus in the top layer of 1.7% (according to Tyurin, DSTU 4289:2004), a slightly acidic reaction of the soil solution with pH 5.5 (ionometrically, DSTU ISO 10390:2022), a low hydrolysed mineral nitrogen content – 10.6 mg kg^{-1} (nitrate nitrogen, DSTU 4725:2007; ammonium nitrogen, DSTU 4729:2007), a high content of mobile phosphorus (P_2O_5) – 193.0 mg kg^{-1}, and an increased content of mobile potassium (K_2O) – 103.0 mg kg^{-1} (both according to Chirykov, DSTU 4115-2002).

Climatic conditions. Due to the climatic changes observed in recent years, the pre-sowing period of winter crops is increasingly characterised by exceeding the average long-term air temperature, the absence or an insufficient amount of precipitation, and their uneven distribution over the territory, which causes the development of drought phenomena. Such weather conditions of the pre-sowing period were observed in 2015, 2016, 2017, and 2019 (Figures 1 and 2). The winter wheat autumn vegetation period was characterised by sufficient heat supply (except for 2015–2016) and excessive precipitation in October (except for 2018–2019), late (more than 1.5–2 weeks later than the average multi-year dates) autumn vegetation termination in 2015, 2017, and 2019. Agrometeorological conditions for overwintering were satisfactory in all years of the experiment due to unusually warm winters and did not have any significant negative impact on winter wheat plants.

The recovery of spring vegetation was early (from the 1st to the beginning of the 2nd ten-day period of March) in 2016, 2017, 2019, and 2020. It should be noted that unfavourable conditions for the growth and development of winter crops in April 2020 were characterised by long frosts in the 1st ten-day period and droughts in the 2nd and the beginning of the 3rd ten-day

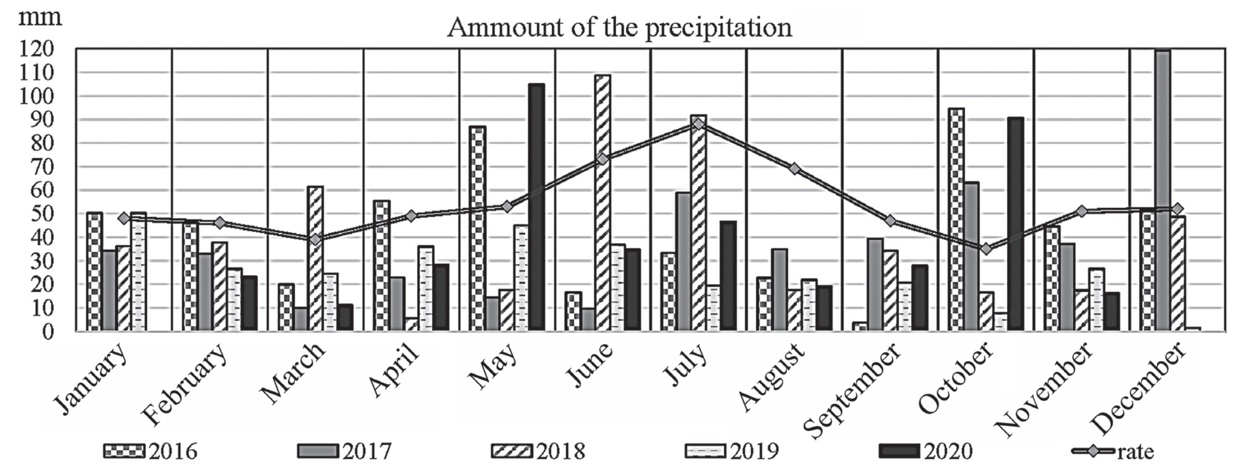

Figure 1. Average monthly precipitation for 2016–2020

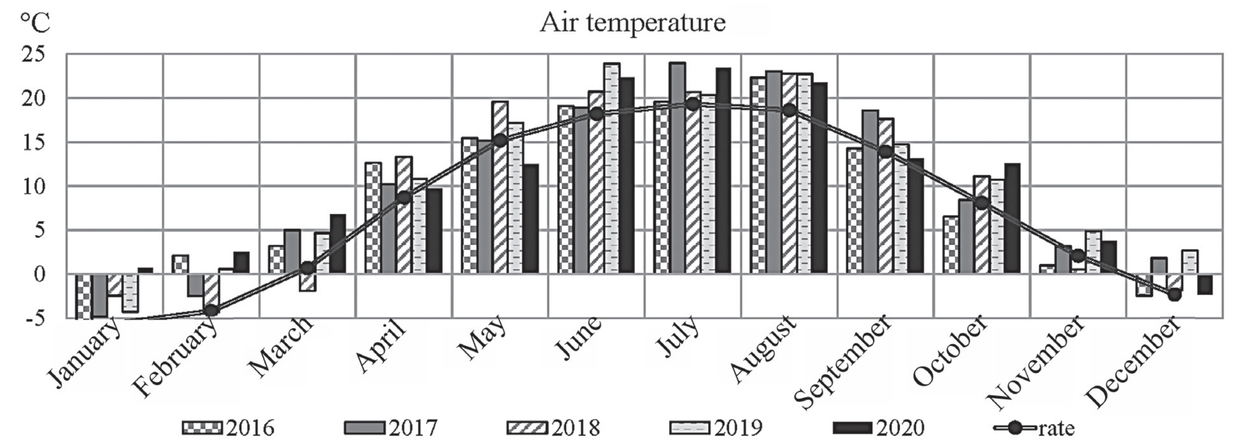

Figure 2. Average monthly air temperature for 2016–2020

periods. The last month of spring was characterised by excessive moisture supply only in 2016 and 2020, while in the other experimental years, a significant deficit of precipitation was observed; the temperature regime of this month exceeded the norm by 2.0–4.3°C in 2018–2019. The summer vegetation period, which includes the formation and ripening of grains, was characterised by an increase in droughts – a deficit of precipitation was observed in all years except 2018, and the excesses of the average long-term values of air temperature in these months (June–July) were noted in 2016–2020. Difficult weather conditions during the harvest in 2018 should be noted with the overtime rainfall from mid- to late July delaying the harvest.

Sampling and methods. Winter wheat cultivation technology was typical of the Forest-Steppe zone. Soil treatment for winter wheat included two-time discing with a disk harrow AGD-2.5, cultivation with a disk weeder KN 3.8, pre-sowing cultivation with the EUROPAK unit, and soil's compaction with a compaction roller 3 KKSH-6.

The preceding winter wheat crop was peas. The winter wheat (*Triticum aestivum* L.) cultivar 'Kraevyd', registered in 2013, which belongs to the valuable types of wheat, classified as medium-season, was grown. Models of cultivation technologies that differed in the rates of applied mineral fertilisers with the background of the preceding crop (pea straw) residues were studied (Table 1).

All models of cultivation technologies were studied under two plant protection systems: minimal (PPS_{min}) and integrated (PPS_{int}). The PPS_{min} included seed treatment before sowing with Vitavax 200 FF (2.5 L t^{-1}) (active substance (a. s.) carboxin, 200 g L^{-1} + thiram, 200 g L^{-1}), crop treatment at BBCH 30 in a mixture with herbicides Caliber (50 g ha^{-1}) (a. s. thifensulfuron-methyl, 500 g kg^{-1} + tribenuron-methyl, 250 g kg^{-1}) and Axial (1.0 L ha^{-1}) (a. s. pinoxaden, 50 g L^{-1}). The PPS_{int} included seed treatment before sowing with Vitavax 200 FF (2.5 L t^{-1}) (a. s. carboxin, 200 g L^{-1} + thiram, 200 g L^{-1}), spraying of crops at BBCH 30 with a mixture of herbicides Caliber (50 g ha^{-1}) (a. s. thifensulfuron-methyl, 500 g kg^{-1} + tribenuron-methyl, 250 g kg^{-1}) and Axial (1.0 l ha^{-1}) (a. s. pinoxaden, 50 g L^{-1}), growth regulator Groom (1.5 L ha^{-1}) (a. s. chlormequat chloride, 750 g L^{-1}), and fungicide Alto Super EC (0.5 L ha^{-1}) (a. s. propiconazole, 250 g L^{-1} + cyproconazole, 80 g L^{-1}). The second treatment of crops was carried out at BBCH 58–59 with fungicide Amistar Xtra (0.75 L ha^{-1}) (a. s. azoxystrobin, 200 g L^{-1} + cyproconazole, 80 g L^{-1}).

Table 1. Fertilisation scheme in winter wheat cultivation technologies

Treatment No.	Cultivation technology	Straw residues of the pre-crop (pea straw)	Fertilisation kg ha^{-1}				
			fertilisation			basic fertilisation	
			N				
			BBCH stage			P_2O_5	K_2O
			23	30	45		
1	Without fertilisers (control)	–	0	0	0	0	0
2	Minimised resource-saving (minRS)	straw residues of the pre-crop	0	0	0	0	0
3	Resource-saving 1 (RS1)	straw residues of the pre-crop	30	30	0	45	45
4	Resource-saving 2 (RS2) with microfertilisers (bifoliar 0.5 L ha^{-1} at BBCH 56–57)	straw residues of the pre-crop	30	30	0	45	45
5	Intensive 1 (I1)	straw residues of the pre-crop	30	60	30	90	90
6	Intensive 2 (I2)	straw residues of the pre-crop	30	60	30	45	45
7	Highly intensive 1 (HI1)	straw residues of the pre-crop	80	60	100	80	100
8	Highly intensive 2 (HI2)	straw residues of the pre-crop	60	75	45	135	135

Phosphorus and potash fertilisers were applied during the main tillage, and nitrogen fertilisers were applied at 23, 30, and 45 stages according to the BBCH scale (Meier, 2001).

The total area of the experimental plot was 36 m^2, and the area of the accounting plot was 28 m^2. There were four replications per treatment, and the placement of plots was sequential. The experiment was based on the split plot design. The sowing rate was 4.5 million germinating seeds per ha. Sowing was carried out at the optimal time depending on the weather conditions, in a continuous row method with a seed planter CH-16A (Ukraine) to a depth of 3 cm. Harvesting was carried out at full maturity (BBCH 92–99) by direct harvesting with a combine harvester SAMPO-130 (Sampo-Rosenlew, Finland) from each treatment with weighing and converting to 100% purity and 14% grain moisture.

Accounting of the grain (main) and straw residues of the pre-crop (pea straw) was carried out separately by weighing. In the treatments where the straw residues of the pre-crop were not introduced, pea straw was removed from the field.

Phenological observations and crop structure analysis were carried out according to the "Methodology for the qualification examination of plant varieties…" (Tkachyk et al., 2016). The determination of crop structure indicators was carried out in the test plots selected from two linear meters in two non-contiguous repetitions in different areas of the plot. The determination of the structural elements of the ear was performed ten times. The plant density of winter wheat was determined at BBCH 34 and 92 according to DSTU 7638:2014. The number of flowers per ear at BBCH 32 and the number of grains per ear at BBCH 92 were determined by the plant biological control method (Kuperman, 1977). The calculations were performed five times. The vitreousness of the grain was determined according to the "Methodology for the qualification examination of plant varieties…" (Tkachyk et al., 2016). The winter wheat grain quality characteristics were determined in the laboratory of the Department of Agroecology and Analytical Research of the NSC IA NAAS by the infrared spectroscopy method using an analyser Infratec 1241 (FOSS). The content of heavy metals and microelements in grains was determined by dry ashing followed by analysis of the ash solution by the atomic absorption method with an atomic absorption spectrophotometer A3 AAS (PERSEE, USA).

Statistical analysis was performed using the analysis of variance (ANOVA) (Statistica, version 6.0). The significance of difference indices was determined by Fisher's test, and the least significant difference (LSD) was determined at the 95% probability level ($P < 0.05$). To assess the relationship between the indicators, the correlational data analysis by the MO Excel program was used.

Results and discussion

Due to the global climate changes observed in Ukraine and the world in recent decades, the main risk that negatively affects agriculture is a lack of moisture, because about 70% of the country's territory constantly suffers from moisture deficiency. Another problem is the temperature stress on plants resulting in the increase in the continentality of the climate. Therefore, to reduce their impact on cereal crops, it becomes necessary to adapt current cultivation technologies to environmental factors.

Adaptive cultivation technologies include the introduction of modern highly productive intensive-type cultivars adapted to the relevant soil and weather conditions, intercropping after the best pre-crop, the optimal fertilisation system, sowing at optimal time, the use of micronutrient fertilisers and growth stimulants, non-commercial crop production, the use of modern integrated plant protection systems against weeds, diseases, and pests, and lodging based on the determination of economic harmfulness thresholds (Yula et al., 2020).

An important factor in increasing the plant's resistance to extreme weather conditions is a balanced fertilisation system based on the results of soil and plant diagnostics taking into account the biological characteristics of crops, critical periods of their growth and development, soil, climatic and weather conditions, and the production and resource potential of the commodity producer. Therefore, determining the optimal fertiliser rates is one of the important tasks of modern agronomic science and practice (Hospodarenko et al., 2021).

The accumulation of the vegetative mass of plants is important in shaping the productivity of winter wheat plants. According to many scientists, the greater the leaf-stem mass of plants, the greater the supply of bioactive substances in it for the formation of reproductive organs and the formation of crop. Therefore, a sufficiently strong development of the vegetative parts of plants and their normal condition is a necessary condition to obtain a high yield. The development of the vegetative mass of plants is a quantitative expression of the favourable growth conditions at one or another stage of development and the conditions for the formation of productivity (Ferrise et al., 2010; Mirosavljevic et al., 2018).

According to the results of the experiment, the formation of winter wheat productivity was studied depending on the cultivation technology, which differed in varying degrees of intensity. The growth dynamics of the vegetative mass calculated per 100 plants was determined by the change in the mass of winter wheat plants with the application of different models of cultivation technologies at BBCH 30, 34, and 65.

It was determined that the accumulation of winter wheat vegetative mass depended on the BBCH stage and cultivation technology. The mass of 100 plants increased from BBCH 30 to 65 when its greatest values were observed (Figure 3). During this period, the mass of 100 plants increased from 116–303 g at BBCH 30 to 938–1727 g at BBCH 65. A positive effect of the use of increasing rates of applied fertilisers according to the cultivation technologies from RS to HI ones on the size of the vegetative mass had been established. At BBCH 65, under the minRS technology, where only straw residues of the preceding crop were used, the vegetative mass of 100 plants increased by 6% compared to the control. Under the RS technologies with the application of $P_{45}K_{45}N_{60}$ on the background of the straw residues of the preceding crop, the vegetative mass increased by 21%, and under the RS2 technology with micro-fertilisers application it increased by 53%. The subsequent application of increasing rates of fertilisers in the control under the I technologies increased by 59–64%, and under the HI ones by 70–85%.

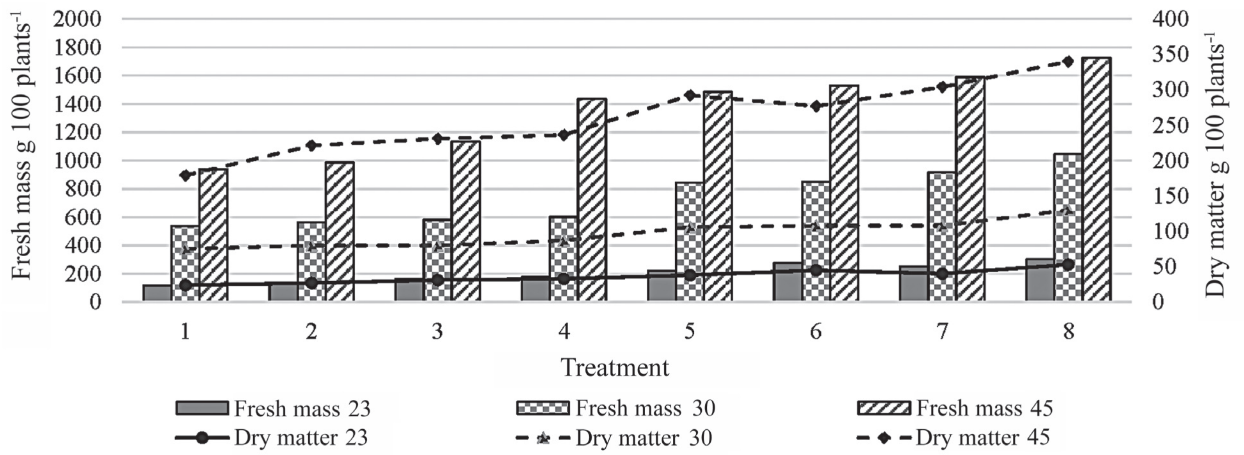

Figure 3. Increase in the winter wheat fresh mass and dry matter per 100 plants during the main BBCH stages under the integrated plant protection system (average for 2016–2020)

Previous studies have shown that different rates of mineral fertilisers had a different effect on the growth and formation of winter wheat plants (Panfilova, Gamayunova, 2018). According to the data of current experiment, a positive correlation was established between the vegetative mass of 100 plants and the grain yield of winter wheat. The correlation coefficient varied from 0.897 to 0.947 at BBCH 30–65. In the same way as the growth of the fresh mass of plants, the amount of dry matter (DM) per 100 plants also increased. The accumulation of DM in winter wheat plants depended on the growth and development stage, cultivation technology, and weather conditions. The value of this indicator increased at BBCH 30–65 and was determined by the amount of applied fertilisers for the cultivation technology. Thus, at BBCH 65, the DM of 100 plants exceeded the control by 1.9 under the HI technology and by 1.5 times under the RS one.

The increase of DM was closely correlated with the winter wheat grain yield – the correlation coefficient varied from 0.86 to 0.89 at BBCH 30–65. The results of the experiment are consistent with the conclusions of other scientists (Hospodarenko et al., 2020). The key to the formation of a highly productive agrocenosis of winter wheat is the creation of an optimal density of productive stems as one of the main elements of winter wheat productivity. Scientists have found that at each BBCH stage, one or another level of a synchronous development of stems is controlled by genetic system and depends on their sensitivity to environmental factors. Therefore, by the regulation of anthropogenic factors, it is possible to form the optimal stalked winter wheat, which will ensure a high sowing productivity (Kolyuchyy et al., 2007; Chugriy, 2020).

Based on the results of the experiment, at BBCH 34, the density of winter wheat stems varied between 884 and 1664 units m^{-2}. At this stage, the density of the total stem stand in the control treatment was at the level of 884 units m^{-2}. Under minRS technology, the stem density was 942 units m^{-2}. According to the technologies from RS to HI that increased fertiliser rates, the total number of stems increased from 1116 to 1664 units m^{-2} depending on the cultivation technology (Table 2).

As shown by analysis of the dynamics of the density of the productive stem stand, during the vegetation period of winter wheat, there is a loss of the density of the stem stand, the value of which depends on both weather conditions and cultivation technology.

Table 2. Influence of winter wheat cultivation technology on the formation of productivity elements under the integrated plant protection system (average for 2016–2020)

Treatment	Fertilisation system	Number of stems at BBCH stage, units m^{-2}		Losses of stems at BBCH 34–92, units m^{-2}	Reduction of stems at BBCH 34–92, %	Number of flowers and grains in the main ear at BBCH stage, units per ear		Losses of flowers at BBCH 32, units	Reduction of flowers at BBCH 92, %
		34	92			32	92		
1	Without fertilisers (control)	844	484	360	43	154	37	117	76
2	Straw residues of the preceding crop	942	526	416	44	157	43	114	73
3	Straw residues of the preceding crop + $P_{45}K_{45}N_{60}$	1116	643	473	42	165	51	114	69
4	Straw residues of the preceding crop + $P_{45}K_{45}N_{60}$ with microfertilisers (bifoliar 0.5 L ha^{-1} at BBCH 56–57)	1164	682	482	41	164	52	112	68
5	Straw residues of the preceding crop + $P_{90}K_{90}N_{90}$	1296	695	601	46	168	56	112	67
6	Straw residues of the preceding crop + $P_{45}K_{45}N_{90}$	1440	692	748	52	165	53	112	68
7	Straw residues of the preceding crop + $P_{80}K_{100}N_{240}$	1624	770	854	53	173	60	113	65
8	Straw residues of the preceding crop + $P_{135}K_{135}N_{180}$	1664	758	906	54	171	58	113	66
	Average	1261.25	656.25			164.47	51.19		
	Sx	60.59	16.21			1.29	1.34		
	CV%	30.38	15.62			4.95	16.57		
	SD	383.23	102.49			8.14	8.48		
	$LSD_{0.05}$	173.10	46.29			3.68	3.83		

Explanation of the treatments in Table 1; Sx – standard error of the arithmetic mean, CV – coefficient of variation, SD – standard deviation, LSD – least significant difference

It was found that the stem density decreased on average by 34–48% at BBCH 34–65 and by 4.7% at BBCH 65–92. The total loss of productive stems of winter wheat at BBCH 34–92 ranged from 360 units m^{-2} in the control to 601 units m^{-2} under the I and up to 906 units m^{-2} under the HI technologies. In total, at BBCH 34–92, from 41% to 54% of the stem of winter wheat grown after peas were lost. At BBCH 92, with the introduction of $P_{45}K_{45}N_{60}$ which provides RS technologies, an average of 484 units m^{-2} of productive stems were saved in the control over the experimental years, and the density of productive stems was 643 units m^{-2}. Under the HI technologies, the increasing rate of fertilisers by three times provided a density of productive stems of 758 units m^{-2}. According to the five-year data, up to BBCH 92, 57% more productive stems were preserved under the HI technologies, 44% under the I and 33% under the RS ones compared to the control.

The second important component of the formation of a highly productive agrocenosis of winter wheat is the graininess of the ear, which is determined by the number of flowers in the growth cone and their number, which during development reaches BBCH 92 (Rozhkov et al., 2016). It was found than the highest potential number of flowers per ear for the winter wheat grown under certain conditions is at BBCH 32 (Kolyuchyy et al., 2007). Based on the results of morphophysiological analysis, the total number of flowers in the main ear of winter wheat ranged from 154 to 173 flowers. It was found that the total number of florets in the spikelet of winter wheat at BBCH 32 varied depending on the applied fertiliser rates under winter wheat cultivation technologies of various intensity. This dependence continued until BBCH 92 in the two-rowed spike (Олійник et al., 2020). It was established that 65–76% of the florets in the spikelets of winter wheat at BBCH 32 were reduced before reaching BBCH 92. For the ears of the one-rowed spike, these losses were higher and ranged from 67% to 84%.

According to the data of current experiment, it was determined that at BBCH 92 (full ripeness), the main spike contained 37–60 grains. It was found that the improvement of winter wheat nutrition conditions under the RS, I, and HI technologies with the involved application of fertilisers allowed one to increase the number of flowers that reached BBCH 92 (seeds) in the two-rowed spikes. The insufficient amount of nutrients in the control (without fertilisers) treatment significantly reduced the number of grains per ear.

The experiment conducted in a typical shallow low-humus chernozem showed that the complex application of intensification factors in winter wheat cultivation technology – high-yielding cultivars, fertilisation system supplemented with sulphur, magnesium, and trace elements, and integrated plant protection – allows one to increase the grain yield up to 7.0 t ha^{-1} (Pol′ovyi et al., 2018). Optimising the existing mineral nutrition systems using post-harvest residues, the seed treatment with bacteria and microfertilisers and cultivated varieties has a positive effect on grain yield and quality (Petrychenko, Korniichuk, 2018). In the present experiment, the analysis of the influence of individual technology elements, such as the fertilisation system, the use of straw residues and plant protection, shows that all the studied elements of the winter wheat cultivation technology had an impact on the formation of the grain yield.

The main factor that increases the winter wheat grain yield is the application of fertilisers (Jankowski et al., 2016). According to the results of the present experiment, the greatest influence on the formation of grain yield had the factor ‘fertilisation system’. In the formation of grain yield, this factor accounted for 79.3%, the PPS for 14.6%, the year for 5.4%, and other factors for 0.7% (Figure 4).

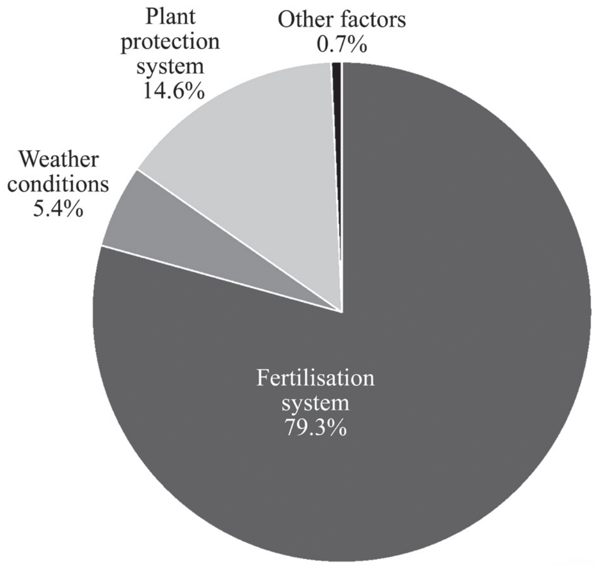

Figure 4. Distribution of the influence of cultivation technology factors (average for 2016–2020)

The grain yield of winter wheat formed due to the natural fertility of the soil in the control (without fertilisers) treatment ranged from 3.72 to 4.22 t ha^{-1}, respectively, under the PPS_{min} and PPS_{int} (Table 3). In terms of prices in 2020, the profit of using of these systems was 406.63 and 448.85 EUR ha^{-1}, respectively.

Applying the minRS technology and using only the straw residues of pre-crop, grain yield was obtained on average of 5 years of 3.96 t ha^{-1} with the PPS_{min} and 4.57 t ha^{-1} with the PPS_{int}. Under these technologies the net profit was 456.32–516.40 EUR ha^{-1}.

The use of RS technologies contributed to an increase in the grain yield compared to the control from 2.60 t ha^{-1} for the PPS_{min} and from 2.91 t ha^{-1} for the PPS_{int}. Under the RS2 technology, the grain yield increased to 2.92 and 3.18 t ha^{-1} depending on the PPS. Under the RS technologies, a profit of 759.34 EUR ha^{-1} was obtained under the PPS_{min} and of 860.34 EUR ha^{-1} under the PPS_{int}. Under the RS2 technology, the PPSs increased the profit to 816.15 and 893.15 EUR ha^{-1}, respectively. The productivity of RS technologies was lower than that of I ones: by applying the I1 and I2 technologies, the grain yield of 8.02 and 8.27 t ha^{-1} was obtained, respectively.

Table 3. Efficiency of the winter wheat cultivation technologies (average for 2016–2020)

Treatment	Fertilisation kg ha^{-1} N	P_2O_5	K_2O	Productivity t ha^{-1}, plant protection system (PPS) minimal	integrated	Extra grain yield due to PPS_{int}[1] t ha^{-1}	Extra grain yield due to fertilisation and straw residues compared to control[2] t ha^{-1}, plant protection system minimal	integrated
1	0	0	0	3.72 a	4.22 a	0.51 a	0.00	0.00
2	0	0	0	3.96 a	4.57 a	0.61 a	0.24 a	0.35 a
3	60	45	45	6.32 b	7.13 b	0.81 b	2.60 b	2.91 b
4	60	45	45	6.64 b	7.40 b	0.76 ab	2.92 b	3.18 b
5	120	90	90	6.97 bc	8.02 b	1.05 b	3.25 b	3.80 b
6	120	45	45	7.06 bc	8.27 bc	1.20 bc	3.34 bc	4.05 bc
7	240	80	100	7.63 c	8.93 c	1.31 c	3.91 c	4.71 c
8	180	135	135	7.67 c	8.91 c	1.24 bc	3.95 c	4.69 c
$LSD_{0.05}$				0.20	0.20			

Notes. Explanation of the treatments in Table 1; [1] – was calculated as the difference between the treatments with and without protection; [2] – was calculated for each PPS separately; different letters mean significant differences between treatments at $P = 0.05$.

Increment of the grain yield to the control treatment amounted to 3.80 and 4.05 t ha^{-1}, and the net profit was 906.46 and 1049.37 EUR ha^{-1}. With the application of PPS_{min}, the grain yield under I technologies decreased to 6.97–7.06 t ha^{-1}; with the application of I1 and I2, it was 8.02 and 8.27 t ha^{-1}, respectively. Compared to the control treatment, the additional grain yield was 3.80 and 4.05 t ha^{-1} with the net profit of 906.46 and 1049.37 EUR ha^{-1}.

Based on the results of the experiment, it was found that the highest winter wheat grain yield was ensured by the HI. Under this technology, which involved the application of $P_{80}K_{100}N_{240}$ mineral fertilisers and the PPS_{int}, the grain yield was 8.93 t ha^{-1} and exceeded the control by 4.71 t ha^{-1}, and the profit reached 972.72 EUR ha^{-1}.

The analysis of the efficiency of individual elements of cultivation technologies, which differed in the intensity and supply of resources, showed that the grain yield increase from the use of fertilisers and the winter wheat straw residues, on average of the experimental data, varied from 0.24 to 3.95 t ha^{-1} for the PPS_{min} and from 0.35 to 4.71 t ha^{-1} for the PPS_{int} (Table 4). Due to the PPS and the application of microfertilisers, the grain yield increased by 0.32 and 0.27 t ha^{-1}, respectively.

Table 4. Indicators of the structure of winter wheat depending on the cultivation technology under the integrated plant protection system (average for 2016–2020)

Treatment	Fertilisation system kg ha^{-1}	Plant height cm	Number, units m^{-2} plants	productive stems	Ear length mm	Grain per ear, units	Productivity of the ear g	Grain: straw
1	Without fertilisers (control)	79 a	234 a	484 a	75 b	33 a	0.91 a	1:1.20
2	Straw residues of the preceding crop	81 a	248 ab	526 a	76 b	35 ab	1.01 a	1:1.22
3	Straw residues of the preceding crop + $P_{45}K_{45}N_{60}$	89 b	272 b	643 b	85 bc	38 b	1.27 b	1:1.23
4	Straw residues of the preceding crop + $P_{45}K_{45}N_{60}$ with microfertilisers (bifoliar 0.5 L ha^{-1} at BBCH 56–57)	85 ab	292 b	682 b	87 b	40 b	1.22 ab	1:1.27
5	Straw residues of the preceding crop + $P_{90}K_{90}N_{90}$	91 b	298 bc	695 b	91 b	40 b	1.35 b	1: 1.28
6	Straw residues of the preceding crop + $P_{45}K_{45}N_{90}$	93 b	301 bc	692 b	93 b	42 bc	1.36 b	1:1.25
7	Straw residues of the preceding crop + $P_{80}K_{100}N_{240}$	92 b	320 c	770 c	99 c	46 c	1.42 c	1:1.30
8	Straw residues of the preceding crop + $P_{135}K_{135}N_{180}$	94 bc	320 c	758 c	98 c	45c	1.40 c	1:1.30
	Average	88.08	285.63	656.25	87.90	37.56	1.25	
	Sx	0.94	7.26	16.21	1.47	1.37	0.04	
	CV%	6.76	16.08	15.62	10.55	23.05	17.87	
	SD	5.95	45.93	102.49	9.27	8.66	0.22	
	$LSD_{0.05}$	2.69	20.74	46.29	4.19	3.91	0.10	

Note. Explanation of the treatments in Table 1; means in columns followed by the same letter are not significantly different at $P = 0.05$; Sx – standard error of the arithmetic mean, CV – coefficient of variation, SD – standard deviation, LSD – least significant difference.

Researchers note the importance of winter wheat crop protection system (Djurle et al., 2018; Švarta et al., 2022; Gaile et al., 2023). In the present experiment, the high efficiency of the PPS_{int} for winter wheat crops was established – its use increased the grain yield by 0.51–1.31 t ha^{-1}. According to this indicator, the efficiency increased from the RS1 to HI technologies.

The analysis of the winter wheat harvest productivity and the main structural elements showed that the high level of crop productivity during the years of the experiment was mainly ensured by a higher density of productive stems and an increase in the productivity of the ear. The introduction of mineral fertilisers, especially nitrogen fertilisers, activated the process of productive tillage, contributed to the increase of grains per ear, the mass of grain per ear, and the grain to straw ratio. Thus, according to the RS1 technology, the average density of productive stems in the experimental years was 643 units m^{-2}, and the productivity of the ear was 1.27 g ear^{-1} at the time when the number of productive stems was 484 units m^{-2} with the productivity of the ear equal to 0.91 g ear^{-1} (Table 4). The improvement of cultivation conditions under applying I1 technology led to an increase in the density of productive stems to 695 units m^{-2} and the ear productivity to 1.35 g ear^{-1}. With the application of HI technologies, the density of the productive stems reached 758–770 units m^{-2}, and the productivity of the ear increased to 1.40–1.42 g ear^{-1}. It was found that the density of productive stems, the length of the ear, the number of ears per ear, the grain size per ear, and the productivity of the ear increased with increasing fertiliser rates under different cultivation technologies.

The best indicators of the structure of winter wheat harvest were characterised by agrocenoses formed applying $N_{240}P_{80}K_{100}$ on the background of the ploughed straw residues of the preceding crop with the PPSint (HI1) due to an increase in the number of productive stems to 770 units m^{-2}, which had 46 units of grains per ear, and the productivity of an ear was 1.42 g.

The competitiveness of grain production largely depends on the quality of products, so it is important to obtain a large yield of high-quality grain during the winter wheat cultivation. The results of the experiment showed that the cultivation technologies, their individual elements, and the weather conditions of the growing season, especially during the period of formation, filling, and ripening of grain (BBCH 70–92), had a significant influence on the formation of winter wheat grain quality.

In all the years of the experiment, except for 2018, the formation and filling of grain took place at a stable moisture deficit (the amount of precipitation was 5–10% of the average annual amount). In 2018, this period was characterised by an uneven distribution of precipitation at BBCH 70–92. This period passed in the conditions of the lack of precipitation until the end of the 3rd ten-day period of June and was replaced by heavy rains when a two-month rainfall fell in two days. The grains formed under such conditions contained less protein and gluten, and the volumetric weight of 1 hectolitre of grain decreased with the application of all cultivation technologies, compared to the previous years of the experiment. The dependence of grain quality on weather conditions was also confirmed by studies of other authors (Zhang et al., 2016; Rozbicki et al., 2019; Sułek et al., 2019).

The analysis of the experimental results showed the significant influence of HI technologies on the winter wheat grain quality, biochemical composition and physical indicators of grain quality (Table 5).

Table 5. Biochemical and physical indicators of winter wheat grain quality depending on the cultivation technology (average for 2016–2020)

Treatment	Protein %		Crude gluten %		Sedimentation		Volume weight kg hl^{-1}		Vitrification %	
	PPS_{min}	PPS_{int}	PPS_{min}	PPS_{int}	PPS_{min}	PPS_{int}	PPS_{min}	PPS_{int}	PPS_{min}	PPS_{int}
1	9.1 a	8.9 a	16.6 a	16.5 a	18.2 a	17.1 a	740 a	746 a	21 a	19 a
2	9.4 a	8.9 a	16.9 a	16.7 a	23.4 ab	20.5 a	741 a	744 a	23 a	19 a
3	10.3 ab	10.2 b	18.9 b	18.6 b	26.6 b	25.8 ab	755 ab	760 b	38 ab	40 b
4	10.0 ab	10.1 b	18.2 b	18.0 ab	27.5 b	25.5 b	760 b	763 b	55 b	44 b
5	11.5 b	11.7 bc	20.3 b	20.8 b	31.6 b	32.5 b	763 b	772 c	68 b	66 c
6	12.1 c	12.6 c	21.7 c	23.0 bc	37.4 c	40.2 bc	767 b	773 c	73 bc	73 c
7	13.3 c	13.8 c	23.3 c	24.0 c	41.8 c	45.3 c	771 bc	771 c	82 c	79 d
8	12.2 c	12.8 c	21.9 c	22.3 b	36.3 bc	45.9 c	765 b	773 c	72 b	76 c
Average	10.98	11.12	19.73	20.00	31.09	30.87	757.68	762.88	53.81	51.93
Sx	0.27	0.31	0.56	0.62	1.97	2.16	4.26	3.97	4.47	4.77
CV%	15.49	17.40	17.93	19.64	40.12	44.30	3.56	3.30	52.57	58.15
SD	1.70	1.93	3.54	3.93	12.47	13.67	26.95	25.14	28.29	30.19
$LSD_{0.05}$	0.77	0.87	1.60	1.77	5.63	6.18	12.17	11.35	12.78	13.64

Note. Means in columns followed by the same letter are not significantly different at $P = 0.05$; PPS – plant protection system; Sx – standard error of the arithmetic mean; CV – coefficient of variation, SD – standard deviation, LSD – least significant difference.

It was found that, on average, during the years of the experiment, applying minRS techology, the winter wheat grains of IV quality class were obtained according to DSTU 3768:2019 (Wheat. Technical conditions) with a protein content of 9.4–8.9% and a gluten content of 16.9–16.7% under the PPS_{min} and PPS_{int} with a protein content of 9.1–8.9% and a gluten content of 6.6–16.5% at the control treatment.

Under the RS technology which included $P_{45}K_{45}N_{60}$ on the background of the ploughed straw residues of the preceding crop under both PPSs, the grain quality corresponded to the IV quality class with 10.3–10.2% protein and 18.9–18.6% gluten. Under the I1 and I2 technologies, it was possible to obtain a high yield of the high-quality grain of III quality class with 11.5–12.6% protein and 20.3–23.0% gluten. Grains under HI1 technology with 13.3–13.85% protein and 23.3–24.6% gluten had the best quality indicators and met the requirements of the II quality class. In the years with favourable weather conditions, using this technology, the grain yield of I quality class was obtained, which contained 14% protein and 28% gluten.

A higher volumetric weight indicates better grain ripening conditions and nutrient saturation (Litke et al., 2018). The grain nature of the winter wheat grown under different intensity technologies varied from 740 g L^{-1} under the control treatment to 765 g L^{-1} under the HI2 with the PPS_{min} and from 746 to 773 g L^{-1}, respectively, under the PPS_{int}.

The vitreousness of the grain is related to the semolina granulation, colour, and protein content and is considered one of the most important characteristics in the sorting affecting the commercial value of the product (Brankovic et al., 2014). Usually, a high vitreousness indicates the increased protein content in the grains. Therefore, it is natural that the grain vitreousness varied depending on the cultivation technology similar to the variation in the protein and gluten content of 21–72% under the PPS_{min} and 19–76% under the PPS_{int}. The vitreousness of the grain was closely correlated with the protein content, crude gluten content, and sedimentation, and the correlation coefficients were 0.95, 0.94, and 0.86, respectively.

An important indicator of grain quality is grain sedimentation, which can be used to indirectly assess the technological and baking properties of flour. The conducted determinations showed that the indicators of grain sedimentation obtained by technologies of various intensities ranged from 23.4 under the minRS to 41.8 under the HI1 compared to 17.1 under the PPS_{min} (control) and from 20.5 to 45.9, respectively, under the PPS_{int}.

The concentration of heavy metals in winter wheat grains is influenced by such soil parameters as pH, organic matter, and the concentration of elements in the upper soil layer (Bermudez et al., 2011). The reaction of plants to the absorption and accumulation of heavy metals and trace elements depends on the cultivar, growing conditions, and the duration of stress (Adrees et al., 2015; Rizwan et al., 2016).

The results of the determination of trace elements and heavy metals showed that the content of copper (Cu) in winter wheat grains was 1.88–2.55 mg kg^{-1} and did not exceed the limit of the maximum permissible concentration (MPC) (Table 6). The amount of this trace element in the grains depending on the cultivation technology did not change significantly due to the low supply of available Cu compounds in the soil. A tendency to decrease the content of Cu in the grain under HI technologies compared to the control treatment was associated with the increased yield and the phenomenon of 'growth dilution'.

The content of zinc (Zn) in the grains varied between 12.35 and 14.5 mg kg^{-1} and did not depend on the cultivation technology and did not exceed the MPC value. Regarding the content of lead (Pb) in the grains, a slight excess of the MPC by 0.10–0.15 mg kg^{-1} was determined, regardless of the cultivation technology, due to the excess of the background content of acid-soluble

Table 6. Results of the chemical analysis of winter wheat grains (average for 2016–2020)

Treatment	Copper (Cu)	Zinc (Zn)	Lead (Pb)	Nickel (Ni)	Cadmium (Cd)	Manganese (Mn)	Iron (Fe)
	Total content mg kg^{-1} DM						
Integrated plant protection system							
1	2.55	12.45	0.65	0.5	0.06	8.6	13.35
2	2.3	13.1	0.6	0.45	0.09	13.75	19.25
3	2.15	12.5	0.65	0.5	0.04	11.35	17.5
4	2.20	12.55	0.6	0.5	0.065	11.55	18.2
5	2.25	12.35	0.65	0.5	0.085	11.5	17.35
6	2.20	12.60	0.6	0.5	0.08	12.5	18.5
7	2.2	14.5	0.6	0.55	0.105	16.2	22.6
8	1.85	13.5	0.6	0.45	0.08	17.6	19.35
MPC	10	50	0.5	0.5	0.1	–	50
Average	2.21	12.90	0.62	0.49	0.08	12.72	17.97
Sx	0.06	0.31	0.01	0.01	0.01	0.74	0.65
CV%	14.31	11.67	8.86	10.24	34.27	28.37	17.79
SD	0.32	1.51	0.05	0.05	0.03	3.61	3.20
$LSD_{0.05}$	0.19	0.90	0.03	0.03	0.02	2.15	1.90

Explanation of the treatments in Table 1; MPC – the maximum permissible concentration; Sx – standard error of the arithmetic mean, CV – coefficient of variation, SD – standard deviation, LSD – least significant difference; DM – dry matter forms of Pb in the soil. Our previous studies conducted in this stationary experiment with different winter wheat cultivars (Давидюк et al., 2019), and studies by other scientists (Makarenko et al., 2009) showed that under the I technologies, the content of Pb in the grains increased compared to the control treatment but was at the level or slightly exceeded the MPC.

The content of Ni in the grains was at the MPC level for all technologies, except for the HI1, where it exceeded the MPC by 0.05 mg kg^{-1}, and the minRS and HI2, where it was lower than the MPC. The content of Cd in the grains varied between 0.06 and 0.085 mg kg^{-1}, and only at the application of HI1 technology a slight 0.005 mg kg^{-1} exceedance of the MPC was detected. The content of Mn in the winter wheat grains increased to 16.2–17.6 mg kg^{-1} under the HI technologies compared to 8.6 mg kg^{-1} in the control treatment. A similar pattern was observed for the Fe accumulation in the grains – its content increased from 13.5 mg kg^{-1} in the control treatment to 19.35–22.60 mg kg^{-1} under the HI technologies but did not exceed the MPC.

Conclusions

As a result of the experiment, a positive impact of the cultivation technologies with increasing intensity on the formation of winter wheat productivity was determined.

1. A positive effect of the increasing rates of applied fertilisers with the cultivation technologies from resource-saving (RS) to highly intensive (HI) on the value of the vegetative mass of winter wheat was established. With the increase in the application of mineral fertilisers, the accumulation level of the dry matter of plants also increased, which was closely correlated with the productivity.

2. As a result of the improvement of winter wheat nutrition conditions with the RS, intensive (I) and HI technologies, an increase in the number of florets in the spikelets at BBCH 32 and grains at BBCH 92 was revealed. By applying these technologies, the number of productive stems preserved up to BBCH 92, and the number of spikelets per ear, the number of grains per ear, and the productivity of the ear increased.

3. The factor ‘fertilisation system’ had the greatest influence on the formation of winter wheat grain yield. In the formation of grain yield, this factor accounted for 79.3%, the plant protection system (PPS) for 14.6%, the weather conditions of the year for 5.4%, and other factors for 0.7%.

4. The highest grain yield was given under the HI technology: the grain yield under the application of $P_{80}K_{100}N_{240}$ mineral fertilisers with the background of the ploughed straw residues of the preceding crop and the integrated PPS was 8.93 t ha^{-1} and exceeded the control by 4.71 t ha^{-1}. Using this technology, grains with the best quality indicators were obtained characterised by 13.3–13.8% protein and 23.3–24.6% gluten content. The net profit was 972.72 EUR ha^{-1}, and the highest net profit was 1049.37 EUR ha^{-1} obtained by applying the I2 technology.

5. There was no significant accumulation of Cu, Zn, Mn, and Fe in the winter wheat grains under application of the studied technologies. Only a slight exceedance of the maximum permissible concentration (MPC) in the grains at a Pb content of 0.10–0.15 mg kg^{-1} (MPC 0.5 mg g^{-1}) was detected.

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