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Formation and realization of the biological productivity potential of soft spring wheat (*Triticum aestivum* L.)

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Abstract. Study is aimed at an in-depth analysis of the biological and agronomically valuable traits of soft spring wheat varieties in combination with different seeding rates in order to determine their adaptability, productivity, and ability to form high-quality grain. The goal of the research was to analyze plant productivity, yield and grain quality from three soft spring wheat varieties and at three different seeding rates. This will allow us to assess the productivity of each of them. The following design was employed for the experimental evaluation of at direct effect of variety in relation to seeding rate (A = Variety; B = Seeding Rate): Variety: Shirokko, Grenny, Uliublena; Seeding Rates: 4,500,000; 5,000,000; 5,500,000 grains ha^{-1}. The accumulation of vegetative mass during the growing season of spring wheat was determined by sampling two non-adjacent repetitions of 0.33 running meters from two adjacent rows, while yield was determined by collecting sheaf samples from each accounting plot. Protein and gluten contents were determined using a SapNIR 2750 infrared analyzer in accordance with DSTU 4117:2007 'Grain and its processed products'. The highest fresh vegetative mass of spring wheat plants was obtained at the milk ripeness stage in the Shirokko variety at a seeding rate of 5,500,000 seeds ha^{-1} – 2.90 kg m². The Shirokko spring wheat variety with a seeding rate of 5,500,000 seeds ha^{-1} ensured the highest grain yield of 5.63 t ha^{-1}, with the highest gluten content in the study – 30.42%, and the highest protein content – 15.64%.

Key words: gluten, protein, seeding rate, variety, vegetative mass, yield.

INTRODUCTION

The grain industry is an important part of the sustainable development process for the agricultural industries and has significant implications for social economic conditions and the development of agricultural exports. One of the most important goals of agricultural production is to produce more high-quality food grains. Wheat is one of the most widely produced food grains in the world, and its proportionate production of the overall total of all grains has been growing; however, the quality of the wheat has not been improving. The amount of high-quality wheat produced has been decreasing. High-quality wheat provides increased flour yields and allows bakers to produce more items (Chernobai et al., 2019).

Spring wheat is of great interest for agricultural production as a bread crop because it is a source of high-quality grain. Under changing weather conditions, the issue of ecological stability of modern intensive soft wheat (*Triticum aestivum* L.*)* varieties has become increasingly acute. Focusing on such varieties, due to an overestimation of their potential productivity, leads to high variability in production (Radchenko et al., 2021; Xu et al., 2023).

Yield formation is a complex multi-stage phenomenon involving many genetically determined photophysical, photochemical, and physiological-biochemical processes at all stages of organogenesis, interacting closely with external environmental factors (Vasylkivskyi et al., 2017; Radchenko et al., 2024).

Spring wheat has a greater sensitivity to growing conditions than other types of wheat and, as such, requires the development of cultivation technologies specific to highly adapted varieties (Hye-Ji, 2016; Hebryn-Baidy et al., 2021). Therefore, further refinement of cultivation technologies, with a focus on spring soft wheat varieties is essential for future production. However, the successful commercialization of these improvements can only be accomplished via the use of new high-yielding varieties, so selecting the most productive variety for each production environment is imperative for increasing crop yield (Pirych et al., 2023; Kovalenko et al., 2025).

Different genotypes of spring wheat vary in vegetation period, growth habit, and environmental requirements. Therefore, they require different agronomic practices, especially seeding rates. Studying variety performance under different seeding rates helps determine optimal parameters for each genotype (Soares et al., 2021).

The biological characteristics of the wheat variety have a major impact on the seeding rate to obtain optimal production. Examples of wheat varieties that produce the highest yield potential are those with high tillering and tall, weakly lodged varieties, which typically require lower seeding rates compared to shorter, semidwarf wheat varieties. The seeding rate should generally be 0.5–1.0 million seeds per hectare higher for short or semi-dwarf wheat varieties than tall wheat varieties, although even short wheat varieties may have reduced yield potential at very high seeding rates (greater than 6 million seeds ha^{-1}) due to limited light penetration and higher utilization of nutrients and water, as well as increased risk of disease (Gyrka & Kulyk, 2016).

Soft wheat achieves the highest yields when forming 400–500 productive stems per m^2. To achieve such density, the optimal seeding rate is 5.0–5.5 million ha^{-1} after better predecessors and 5.5–6.5 million ha^{-1} after worse ones (Yula & Drozd, 2020).

According to analysis, it was found that the biological potential for crop yields from different varieties and hybrids has been reached only 40–75% in the last 20 years (Goher & Akmal, 2021; Trotsenko et al., 2023). The two primary aspects which lead to an increase in grain yield include the use of newer varieties, as well as the use of higher productive technology. In order for spring wheat varieties to produce as much as possible, there should be a focus on conducting Morphophysicological analyses which would allow for the development of ideal agro-phytocenoses based upon high productivity. Another key to improving the sustainablility of grain production is through increasing the acreage of high yield domestics (i.e. someone in your area) spring wheat varieties. Understanding the Genetics of spring wheat productivity and grain quality is an essential area for improving grain production (Herasymchuk et al., 2022; Sobko et al., 2023)

The study is aimed at a comprehensive evaluation of the biological and agronomically valuable traits of spring bread wheat varieties in combination with different seeding rates to determine the patterns of productivity and grain quality formation. The scientific novelty of the research lies in identifying the specific features of the realization of the genetically determined potential of modern varieties depending on plant density, determining the interaction between varietal characteristics and seeding rates, and substantiating the optimal parameters of crop stand formation that ensure the maximum realization of the crop productivity potential. The obtained results will deepen scientific understanding of the response of spring bread wheat varieties to different agrocenosis densities and provide a scientifically grounded basis for optimizing cultivation technology elements aimed at increasing yield and obtaining high-quality grain.

MATERIALS AND METHODS

Field stationary trials involving spring wheat (*Triticum aestivum* L.) were established at the experimental plots of the Educational and Scientific Centre of Sumy National Agrarian University. The experimental plots were established in the Sumy district of Sumy region in Ukraine, and were located at a latitude and longitude of 50°52.742'N; 34°46.159'E, with an elevation of 137.7 m above sea level (50°52'46.6"N; 34°46'07.8"E), as defined by (2023) Google (data ©2023). This research will be conducted from 2023–2025.

The experiments assessing varietal characteristics and optimal seeding rates of spring wheat for productivity and quality indicators followed the scheme: Factor A – varieties: Shirokko, Grenny, Uliublena Factor B – seeding rates: 4,500,000 grains ha^{-1}, 5,000,000 grains ha^{-1}, 5,500,000 grains ha^{-1}.

The technology of spring wheat cultivation followed standard practices for the Forest-Steppe zone of Ukraine, except for the specific technological elements studied in the trial. Soybean was the preceding crop. Planting was performed with a Klen–1.5 seed drill when the soil temperature reached 6–8 °C. seeds were placed in rows spaced 15 cm apart at a depth of 3–4 cm. The application of mineral fertilizers at a dose of $N_{32}P_{32}K_{32}$ was carried out simultaneously with sowing. Nitroammophoska was used – a complex mineral fertilizer containing three main elements: nitrogen, phosphorus, and potassium (NPK). Each nutrient is present at approximately 16 ± 1%, and the total content of active substances is 48% of the fertilizer’s mass. The experiment was conducted under field conditions. Experimental treatments were arranged systematically. The trial was established according to a two-factor design, including nine treatment combinations (3 varieties × 3 seeding rates). Each treatment was represented by three replications, resulting in a total of 27 experimental plots. The total area of each plot was 45 m², of which 30 m² constituted the accounting area. The total experimental area was 1,215 m², while the total accounting area was 810 m².

Phenological assessments were conducted in accordance with the guidelines outlined in the Methodology of State Variety Testing of Agricultural Crops (Rozhkov et al., 2016). The accumulation of vegetative mass during the spring wheat growing season was determined by collecting samples from two non-adjacent repetitions of 0.33 linear meters from two adjacent rows. Plant height at each developmental stage was measured using a ruler from the soil surface to the highest point of the plant. Plant samples were collected during the tillering, stem elongation, heading, and milk ripeness stages.

During the vegetation period of spring wheat varieties, leaf area was determined. The area of an individual leaf was calculated using its length, width, and a conversion coefficient of 0.67, which is used for cereal crops with linear (elongated) leaf shapes. The leaf area was calculated using the formula: $A = L \times W \times C$, where A – leaf area (cm^2); L – leaf length (cm); W – leaf width (cm); C – conversion coefficient (0.67) (Rozhkov et al., 2016).

Protein and gluten contents were determined using a SapNIR 2750 infrared analyzer in accordance with DSTU 4117:2007 'Grain and its processed products' (DSTU 4117:2007, 2017).

Statistical analyses were performed using the software package Statistica 10.0 (StatSoft Inc., Tulsa, OK, USA). The effects of genotype (variety), seeding rate, and their interaction were evaluated using two-way analysis of variance (ANOVA). Statistical significance of the studied factors was determined using Fisher's F-test, while differences between mean values were assessed using the Least Significant Difference ($LSD_{0.05}$). Differences were considered statistically significant at $P < 0.05$. Primary data were processed mathematically using Microsoft Excel (Nadykto, 2017).

The soil on the trial area is classified as typical chernozem with a deep medium loamy structure and has the following characteristics: humus content ranges from 4.1–4.3% (according to Tiurin), soil pH varies between 6.2 and 6.5. Nutrient concentrations in the soil are as follows: nitrogen (by Kornfield) – 128.5 mg kg^{-1}; phosphorus and potassium (by Chirikov) – 211.6 mg kg^{-1} and 81.1 mg kg^{-1}, respectively.

The mean air temperature per day in 2023 amounted to 9.1 °C. The absolute maximum temperature of 36 °C was recorded in the first ten days of August, while the minimum temperature of -19 °C occurred in the first ten days of January. In the 2022–2023 growing season, cumulative precipitation reached 637 mm. Distribution by season: autumn 2022 – 176 mm; winter 2022–2023 – 102 mm; spring 2023 – 86 mm; summer 2023 – 273 mm.

In 2024, the average daily air temperature was 9.8 °C. The absolute maximum of 36 °C was recorded in the second ten days of July, while a minimum of -21 °C was observed in late January. In the 2023–2024 cropping year, cumulative precipitation reached 491 mm. Seasonal distribution: autumn 2023 – 222 mm; winter 2023–2024 – 93 mm; spring 2024 – 94 mm; summer 2024 – 41 mm.

The average annual daily temperature in 2025 was 10.4 °C. Temperatures peaked at 35 °C in early July, while the lowest value of −16 °C was registered in late February. Total precipitation in the 2024–2025 agricultural year was 450 mm. Seasonal distribution: autumn 2024 – 144 mm; winter 2024–2025 – 21 mm; spring 2025 – 96 mm; summer 2025 – 195 mm.

In general, 2023 and 2025 were the most favorable years for crop productivity. In contrast, 2024 was marked by arid conditions, with limited rainfall and pronounced temperature fluctuations throughout the growing season.

RESULTS AND DISCUSSION

One of the most important biological factors determining plant viability is the process of photosynthesis, which plays a significant role in the formation of crop yields. It is known that photosynthetic productivity is assessed based on two key indicators: the total leaf area and the intensity of photosynthetic processes. The main factors influencing the size of the assimilating leaf surface during crop cultivation are technological measures and vegetation conditions (Klymyshena et al., 2024; Sikora, 2024).

The main indicator of crop condition, as a photosynthetic system, is leaf growth and development expressed by leaf area. The formation of leaf area is largely influenced by leaf size, the functioning period of the leaf, and the duration of active vegetation. A crucial factor is maintaining leaf functionality throughout the entire growing season to achieve high yield levels (Bilousova & Keneva, 2023).

According to literature, to achieve high grain crop yields, the leaf area should be 50,000–60,000 m² ha^{-1}. This ensures sufficient light exposure and moisture availability for the plants (Wang et al., 2020).

The data shown in Table 1 demonstrate that the development of leaf surface area in spring wheat was significantly influenced by varietal traits as well as by the seeding rate. In all experimental treatments, a consistent increase in leaf surface area was observed from the tillering stage to the heading stage. An increase in the seeding rate from 4,500,000 to 5,500,000 seeds per hectare was accompanied by an increase in leaf surface area at all stages of plant development. In particular, during the heading stage, the increase in leaf surface area averaged 2,000–2,700 m² ha^{-1} depending on the variety.

Varietal characteristics significantly affected the formation of leaf area, indicating different genotype responses to crop density and differences in the realization of their morphophysiological potential. The largest leaf area during all growth stages was formed by the variety Shirokko, with a maximum value of 41.3 thousand m² ha^{-1} at the heading stage under a seeding rate of 5,500,000 seeds ha^{-1}. This may be attributed to the genetically determined ability of the variety to maintain intensive leaf apparatus development under increased crop density, thereby promoting more efficient utilization of photosynthetically active radiation, accumulation of assimilates, and realization of productivity potential. The smallest leaf area at all developmental stages was observed in the variety Grenny, which is likely associated with its genetically determined growth characteristics and lower plasticity in response to changes in crop density. Increased competition among plants for light, moisture, and nutrients with higher seeding rates restricts leaf apparatus development, accelerates leaf senescence, and reduces the efficiency of the photosynthetic system.

The Uliublena variety occupied an intermediate position in terms of assimilatory surface development, demonstrating a stable increase in leaf surface area with increasing seeding rate but remaining inferior to Shirokko.

Analysis of variance showed that variety and seeding rate significantly affected leaf area during the tillering, stem elongation, and heading stages ($F = 66.775–150.303$; $p < 0.001$). The greatest influence on the studied trait was exerted by the factor ‘variety’, as confirmed by high F-values. The interaction ‘*variety × seeding rate*’ was statistically insignificant at all developmental stages ($F = 0.135–1.456$; $p = 0.257–0.967$). $LSD_{0.05}$ values ranged from 0.27 to 0.57 for the factor ‘variety’, 0.27 to 0.57 for the factor ‘seeding rate’, and 0.47 to 0.98 for their interaction, confirming significant differences between the mean values of the main factors (Table 1).

Table 1. Dependence of spring wheat leaf area on varietal characteristics and seeding rates, thousand m² ha^{-1} (average for 2023–2025)

Variety	Seeding rate, seeds ha^{-1}	Leaf surface area by phase		
		tillering	stem elongation	earing
Shirokko	4,500,000	7.5	28.6	39.1
	5,000,000	8.4	29.3	40.0
	5,500,000	9.6	30.4	41.3
Grenny	4,500,000	5.9	26.1	36.7
	5,000,000	6.6	26.7	37.2
	5,500,000	7.4	27.8	37.9
Uliublena	4,500,000	6.7	27.5	38.0
	5,000,000	7.7	28.2	38.7
	5,500,000	8.9	29.1	39.4
$LSD_{0.05}$:				
variety		0.27	0.31	0.57
seeding rate		0.27	0.31	0.57
interaction		0.47	0.53	0.98
F-value:				
variety		105.353	150.303	56.030
seeding rate		111.706	66.775	17.545
interaction		1.456	0.135	0.667
p-value:				
variety		< 0.001	< 0.001	< 0.001
seeding rate		< 0.001	< 0.001	< 0.001
interaction		0.257	0.967	0.623

Plant height performs important agronomic and biological functions throughout plant ontogenesis and is closely associated with other traits and properties, primarily lodging resistance, nutrient uptake efficiency, productivity, and product quality. The height of wheat plants has a genetic basis and high heritability (Velimirović et al., 2023).

Achieving a high genetic yield potential of more than 8–10 t ha^{-1} is possible only in varieties with a strong and relatively short stem. The optimal plant height that ensures maximum yield, high lodging resistance, and tolerance to adverse environmental conditions generally ranges from 85 to 95 cm (Fanin & Lytvynenko, 2023).

The results showed that plant height increased consistently with increasing seeding rates throughout all growth stages. At the tillering stage, plant height was the lowest and ranged from 18.8–22.2 cm for Shirokko, 18.1–20.2 cm for Grenny, and 21.3–23.5 cm for Uliublena. The tallest plants were formed by the variety Uliublena (23.5 cm at 5,500,000 seeds ha^{-1}), indicating its higher morphophysiological plasticity and ability to adapt to changes in crop density.

The most intensive increase in plant height was observed during stem elongation. With increasing seeding rates, plant height of Shirokko increased from 46.4 to 55.7 cm, Grenny from 41.6 to 48.7 cm, and Uliublena from 61.3 to 66.7 cm. This trend is associated with enhanced competition for light, which stimulates internode elongation, whereas the magnitude of this response is determined by varietal genetic characteristics.

Maximum plant height was reached at the heading stage. As the seeding rate increased, plant height rose from 80.2 to 85.3 cm in Shirokko, from 73.4 to 79.6 cm in Grenny, and from 90.2 to 98.4 cm in Uliublena. The tallest plants were recorded in Uliublena (98.4 cm) at a seeding rate of 5,500,000 seeds ha^{-1} (Fig. 1). These results indicate that final plant height is determined by a combination of varietal genetic characteristics and crop density, while the response to increased seeding rates represents an adaptation mechanism to competition for light.

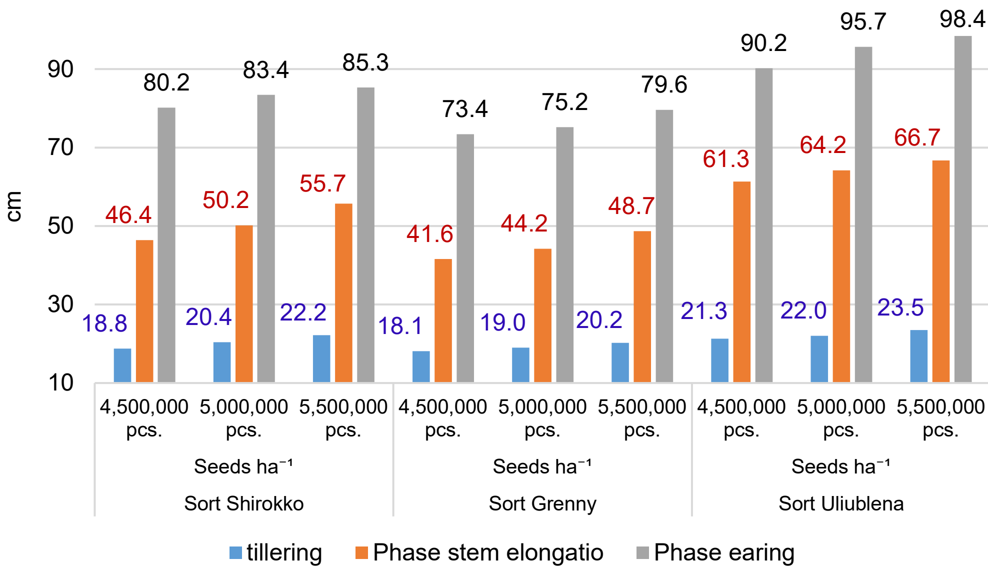

Figure 1. Dependence of spring wheat plant height on varietal characteristics and seeding rates, cm (average for 2023–2025).

The variety Uliublena, which produced the tallest plants during stem elongation and heading, was characterized by more intensive linear growth and a greater ability to realize its genetically determined potential under optimal crop density. This response indicates substantial morphophysiological plasticity and the capacity to adapt to changes in the competitive environment. These findings are consistent with the conclusions of Schmitz & Ransom (2021), who reported that varieties with high phenotypic plasticity respond more effectively to changes in crop density, utilize light, water, and mineral resources more efficiently, maintain higher growth intensity, and ensure more stable realization of productivity potential. This confirms that varietal response to seeding rate is the result of a complex interaction between genetic characteristics and agrocenosis factors, and optimization of plant density should be carried out considering the biological properties of a specific variety.

According to ANOVA, both variety and seeding rate significantly affected plant height at all studied growth stages ($p < 0.001$). The interaction '*variety × seeding rate*' was insignificant ($p > 0.05$). $LSD_{0.05}$ values ranged from 0.51 to 2.37 cm, indicating statistically significant differences between the mean values of the main factors.

It is important to note that excessive increases in seeding rate may lead to anthropogenic constraints on the development of certain generative parameters. Ma et al. (2018), demonstrated that excessive plant density negatively affects spike size and grain density due to intensified intraspecific competition. Therefore, optimization of cultivation technology requires not only appropriate seeding rates but also their alignment with varietal potential.

The findings regarding the effects of varietal traits and seeding rate on the morphometric characteristics of spring wheat are in agreement with numerous international studies. These studies have shown that higher plant density in barley and wheat stands intensifies competitive growth, resulting not only in increased plant height but also in modifications of root system architecture and overall productivity (Hecht et al., 2016). Likewise, Zhang et al. (2023a) identified seeding rate as a crucial agronomic factor influencing canopy light interception and, consequently, photosynthetic performance and the intensity of vegetative development.

$LSD_{0.05}$ values confirmed the statistical significance of the effects of variety, seeding rate, and their interaction on plant height, which aligns with conclusions from recent studies emphasizing the importance of optimizing crop density to enhance cereal productivity (Zhu et al., 2022; Liu et al., 2025).

Optimal provision of all factors necessary for plant growth and development creates the conditions for forming a general habitus that ensures maximum productivity. Absolute values of aboveground biomass accumulation serve as external indicators of internal physiological processes, and the rate of biomass growth makes it possible to reliably assess the influence of various factors on the plant. According to the research of Panfilova (2023), the accumulation of raw aboveground biomass by wheat plants during the spring-summer vegetation period depended on several factors, including varietal biological characteristics, and experimental treatments. The most intensive biomass accumulation occurred between the stem elongation and heading stages. On average over the years of the study, at the end of the growing season, plants accumulated from 2.17 to 2.36 kg m^2 of raw biomass.

The results demonstrated that the accumulation of fresh vegetative biomass in spring wheat was significantly influenced by the interaction between genotype and seeding rate. At the tillering stage, the highest vegetative biomass was recorded for the variety Shirokko (0.59 kg m^{-2}) at a seeding rate of 5,500,000 seeds ha^{-1}, whereas the varieties Grenny and Uliublena exhibited lower values. This indicates a more intensive initial growth of Shirokko plants, likely associated with greater growth vigor, faster leaf area development, and more efficient utilization of available resources during the early stages of organogenesis. At the same time, increasing the seeding rate promoted higher total biomass accumulation per unit area due to a greater number of plants, despite intensified competition among them.

At the stem elongation stage, fresh vegetative biomass increased considerably. In Shirokko, biomass ranged from 1.58 to 1.70 kg m^{-2}; in Grenny, from 1.47 to 1.57 kg m^{-2}; and in Uliublena, from 1.52 to 1.64 kg m^{-2}. The maximum value (1.70 kg m^{-2}) was again observed in Shirokko at a seeding rate of 5,500,000 seeds ha^{-1}. Intensive biomass accumulation at this stage resulted from active stem elongation, rapid expansion of leaf area, and high photosynthetic activity. The superiority of Shirokko was likely due to its ability to maintain a larger assimilatory surface, ensuring more efficient accumulation of organic matter even under increased crop density.

During the heading stage, fresh vegetative biomass continued to increase. In Shirokko, biomass ranged from 2.65 to 2.78 kg m^{-2}; in Grenny, from 2.46 to 2.62 kg m^{-2}; and in Uliublena, from 2.60 to 2.71 kg m^{-2}. The highest value (2.78 kg m^{-2}) was recorded in Shirokko under the highest seeding rate. This indicates that this variety more effectively realized its photosynthetic potential during the critical period of reproductive organ formation, when dry matter accumulation largely determines future crop productivity. Conversely, lower biomass values in Grenny may be attributed to its smaller leaf area and lower vegetative growth intensity, as established in previous stages of the study.

At the milk ripeness stage, the maximum fresh vegetative biomass values were obtained: 2.79–2.90 kg m^{-2} for Shirokko, 2.64–2.77 kg m^{-2} for Grenny, and 2.71–2.83 kg m^{-2} for Uliublena. The highest value (2.90 kg m^{-2}) was recorded in Shirokko at a seeding rate of 5,500,000 seeds ha^{-1} (Fig. 2). The superiority of this variety indicates its high capacity to maintain active functioning of the assimilatory apparatus throughout a prolonged growing season and to utilize environmental resources efficiently. However, increased vegetative biomass does not always directly correlate with final grain yield, since the efficiency of assimilate redistribution to reproductive organs during grain filling is crucial. Therefore, the higher biomass accumulation observed in Shirokko may indicate substantial productivity potential only if accompanied by efficient source–sink relationships between vegetative organs and the spike.

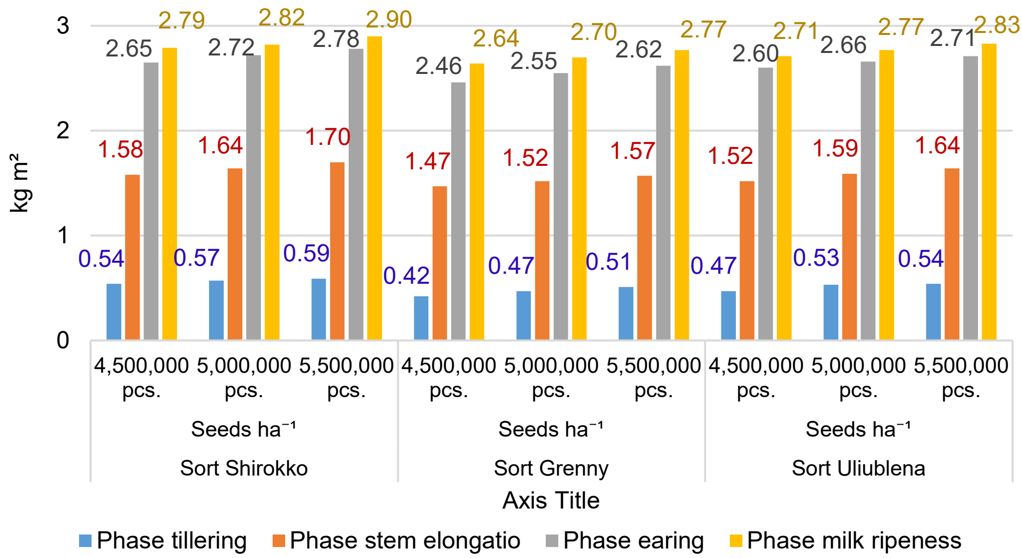

Figure 2. Dynamics of raw aboveground biomass formation in spring wheat depending on varietal characteristics and seeding rates, kg m^{-2} (average for 2023–2025).

The obtained results demonstrate a consistent increase in fresh vegetative biomass of spring wheat from the tillering stage to milk ripeness, which corresponds to modern concepts of biomass accumulation dynamics in cereal crops throughout ontogenesis (Wang et al., 2024). It was established that biomass increase with higher for sowing of 5,500,000 grains ha^{-1} confirms the findings of Zhang et al. (2023b), regarding optimal plant density for more efficient use of light and spatial resources, while varietal differences, particularly the maximum values recorded in Shirokko, are consistent with Morgun et al. (2019), concerning the influence of genetic traits on wheat growth and photosynthetic activity. Moreover, the significant interaction effect '*variety × seeding rate*' confirms the conclusions of Zaima et al. (2024), on the need to align varietal biological characteristics with cultivation technology parameters, and the observed biomass increase up to the milk ripeness stage corresponds to Feng et al. (2021), who noted that excessive vegetative growth at later stages may have both positive and limiting effects on yield formation.

Statistical analysis confirmed a significant influence of all studied factors on fresh vegetative biomass formation, supporting modern international concepts of factor-regulated growth processes in cereal crops (Yousefi et al., 2025). High F-values indicated the decisive effect of variety ($F = 51.429–66.118$) and seeding rate ($F = 34.875–52.774$) on biomass accumulation throughout the growing season. The interaction '*variety × seeding rate*' was not statistically significant ($F = 0.265–2.349$; $p = 0.093–0.897$). $LSD_{0.05}$ values ranged from 0.019 to 0.051 kg m^{-2}, confirming significant differences between the means of the main factors.

Studying varietal characteristics enables more accurate selection of cultivars suited to specific growing zones, taking into account soil fertility. Today, without evaluating a cultivar's stability and plasticity, it is impossible to obtain high returns even when using advanced technologies (Ishchenko, 2021).

The results showed that spring wheat grain yield was significantly determined by both varietal characteristics and seeding rate. This indicates that varietal responses to changes in plant density were genotype-specific and depended on their ability to realize productivity potential under different levels of intraspecific competition.

In the variety Shirokko, grain yield increased from 5.47 to 5.63 t ha^{-1} as the seeding rate increased from 4,500,000 to 5,500,000 seeds ha^{-1}. The greatest yield increase (+0.16 t ha^{-1}) was obtained at the highest seeding rate, indicating a strong positive response of this variety to denser stands. This response is likely associated with the ability of Shirokko to maintain high photosynthetic productivity, efficiently utilize light, water, and mineral resources, and compensate for increased plant competition through the formation of a larger leaf area and greater vegetative biomass, as demonstrated in previous stages of the study.

The variety Grenny exhibited the lowest grain yield among the studied genotypes, ranging from 4.31 to 4.48 t ha^{-1}. Despite a positive response to increasing seeding rate, the absolute yield increase was limited, indicating lower morphophysiological plasticity and less efficient resource utilization under higher plant densities. The smaller leaf area and lower biomass accumulation observed in this variety likely restricted photosynthetic activity and assimilate supply to the spike, negatively affecting the realization of its productivity potential.

For the variety Uliublena, grain yield ranged from 4.60 to 4.68 t ha^{-1}. Increasing the seeding rate to 5,000,000 seeds ha^{-1} resulted in a yield increase of 0.07 t ha^{-1}, whereas further increasing the density to 5,500,000 seeds ha^{-1} had little effect on productivity (+0.08 t ha^{-1} compared with the minimum seeding rate). This indicates that an optimal crop density was already achieved at 5,000,000 seeds ha^{-1}, after which the positive effect of increasing plant number was offset by stronger competition for resources. Despite producing taller plants, Uliublena did not provide a proportional increase in grain yield, suggesting that intensive vegetative growth is not always accompanied by more efficient assimilate redistribution to reproductive organs.

Thus, the highest grain yield (5.63 t ha^{-1}) was produced by Shirokko at a seeding rate of 5,500,000 seeds ha^{-1}, whereas the lowest yield (4.31 t ha^{-1}) was obtained from Grenny at 4,500,000 seeds ha^{-1} (Fig. 3). These results indicate that the optimal seeding rate is variety-specific, and its effectiveness depends on the level of morphophysiological plasticity of the genotype, its ability to maintain photosynthetic productivity, and the efficiency of converting accumulated biomass into grain yield. The integrated interaction of these processes ensures maximum realization of the genetic productivity potential of spring wheat varieties.

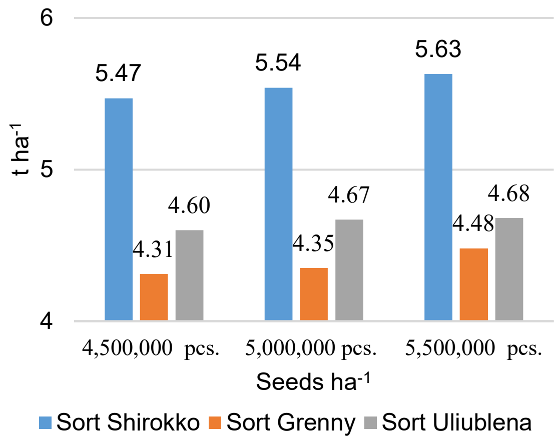

Figure 3. Grain yield of spring wheat depending on varietal characteristics and seeding rates (average for 2023–2025), t ha^{-1}.

Analysis of variance showed that yield variation was mainly determined by varietal characteristics and seeding rate ($p < 0.001$), whereas their interaction had no statistically significant effect ($p = 0.076$). F-values indicated a stronger influence of variety (266.837) compared with seeding rate (33.089). $LSD_{0.05}$ values were 0.036 t ha^{-1} for the main factors and 0.063 t ha^{-1} for their interaction.

Ensuring stable grain production has long been, and continues to be, a key priority. This drives producers to implement practices aimed not only at increasing yield but also at substantially improving essential grain quality parameters. However, the harvested grain frequently exhibits relatively low quality (Macholdt & Honermeier, 2017).

In our study, the wet gluten content in spring wheat grain significantly depended on both varietal characteristics and seeding rate, varying within the range of 26.03–30.42%. The highest values were recorded for the variety Shirokko: 29.28% at a seeding rate of 4,500,000 seeds ha^{-1}, 29.75% at 5,000,000 seeds ha^{-1}, and 30.42% at 5,500,000 seeds ha^{-1}. In the variety Grenny, gluten content amounted to 26.03%, 26.37%, and 26.82%, respectively, whereas in Uliublena it reached 28.10%, 28.52%, and 28.97%. The maximum value (30.42%) was recorded in Shirokko at a seeding rate of 5,500,000 seeds ha^{-1} (Table 2).

The obtained results indicate that the formation of the gluten complex is determined not only by the genetic characteristics of the variety but also by plant responses to crop density. The superiority of Shirokko is likely associated with its greater ability to accumulate nitrogen-containing compounds in the grain and to more efficiently transform them into storage proteins of the endosperm, primarily gliadins and glutenins, which determine both the quantity and technological properties of gluten. A moderate increase in seeding rate apparently contributed to the optimization of crop structure, more efficient utilization of photosynthetically active radiation, and enhanced translocation of assimilates and nitrogen compounds into the grain during the grain-filling period. At the same time, the observed varietal differences indicate different efficiencies of nitrogen metabolism and nitrogen remobilization processes from vegetative organs to the grain, which largely determine the baking quality of wheat grain.

A similar trend was observed for protein content, which varied from 13.41% to 15.64% depending on variety and seeding rate. The highest protein content was formed by the variety Shirokko: 14.25% at a seeding rate of 4,500,000 seeds ha^{-1}, 15.20% at 5,000,000 seeds ha^{-1}, and 15.64% at 5,500,000 seeds ha^{-1} (Table 2). The higher protein content of this variety is likely the result of a combination of genetically determined storage protein synthesis intensity and a more efficient supply of photosynthetic products and nitrogen compounds during grain filling. Furthermore, the positive response to increased seeding rate indicates that under the conditions of this experiment, higher crop density did not lead to resource deficiency; on the contrary, it ensured more efficient utilization of the agroecological potential and promoted protein accumulation. This confirms that optimal plant density is an important component of cultivation technology that, together with varietal genetic characteristics, determines not only grain yield but also technological grain quality.

Table 2. Qualitative indicators of spring wheat grain depending on the influence of varietal characteristics and sowing rates (average for 2023–2025)

Variety	Seeding rate, seeds ha^{-1}	Gluten content, %	Protein content, %
Shirokko	4,500,000	29.28	14.25
	5,000,000	29.75	15.20
	5,500,000	30.42	15.64
Grenny	4,500,000	26.03	13.41
	5,000,000	26.37	13.52
	5,500,000	26.82	13.74
Uliublena	4,500,000	28.10	14.16
	5,000,000	28.52	14.37
	5,500,000	28.97	14.84
$LSD_{0.05}$:			
variety		0.18	0.19
seeding rate		0.18	0.19
interaction		0.31	0.32
F-value:			
variety		830.547	< 0.001
seeding rate		61.205	< 0.001
interaction		0.840	0.518
p-value:			
variety		140.756	< 0.001
seeding rate		40.878	< 0.001
interaction		7.385	0.001

A slightly lower protein content was obtained in the Uliublena variety: 14.16%, 14.37%, and 14.84%, respectively. The lowest protein content was recorded in the Grenny variety: 13.41%, 13.52%, and 13.74%, respectively (Table 2).

The results of the analysis of variance showed that variety and seeding rate had a significant effect on gluten and protein content in spring wheat grain ($p < 0.001$). The F-values for the factor '*variety*' were considerably higher than those for the factor '*seeding rate*', indicating the dominant role of genotype in determining grain quality traits. The interaction '*variety × seeding rate*' was not significant for gluten content ($F = 0.840$; $p = 0.518$), whereas it was statistically significant for protein content ($F = 7.385$; $p = 0.001$). The Least Significant Difference ($LSD_{0.05}$) ranged from 0.18–0.31% for gluten content and 0.19–0.32% for protein content, confirming the reliability of the observed differences among treatment means.

Table 3 presents the results of Pearson correlation analysis characterizing the relationships between yield and the main grain quality indicators of spring wheat-protein and gluten content-averaged over 2023–2025. A strong positive correlation between yield and gluten content was established, particularly for the varieties Shirokko (*r* = 0.923) and Grenny (*r* = 0.971), which is consistent with the results of recent international studies demonstrating the possibility of combining high productivity with improved baking properties of grain due to genetic and physiological characteristics of the variety (Marcos-Barbero et al., 2021; Kiseleva et al., 2025).

Table 3. Results of Pearson correlation analysis characterizing the degree of relationship between yield indicators and quality traits of spring wheat grain (average for 2023–2025)

Variety	Yield, t ha^{-1} – Gluten content, %	Yield, t ha^{-1} – Protein content, %	Gluten content, % – Protein content, %
Shirokko	0.923	0.782	0.855
Grenny	0.971	0.458	0.423
Uliublena	0.897	0.429	0.713

The correlation between yield and protein content was less stable and varied depending on the variety (*r* = 0.429–0.782), which corresponds to modern concepts of the so-called *grain protein deviation* phenomenon, where protein accumulation largely depends on nitrogen nutrition conditions and climatic factors, as well as the genetic ability of a variety to efficiently utilize nitrogen (Mosleth et al., 2020; Richard et al., 2025).

A strong positive correlation between gluten and protein content was also established, particularly for the Shirokko variety (*r* = 0.855) and Uliublena (*r* = 0.713), which confirms modern views on the common biochemical nature of these grain quality indicators. Overall, the obtained results are consistent with data from international researchers who emphasize the increasing importance of varietal adaptability in ensuring stable yield and high grain quality (Agapie et al., 2025).

CONCLUSIONS

1. It was established that varietal characteristics and seeding rate significantly influence leaf area formation, plant growth, vegetative biomass accumulation, grain yield, and technological grain quality traits of spring wheat. The largest leaf area at the heading stage was formed by the variety Shirokko at a seeding rate of 5,500,000 seeds ha^{-1}, reaching 413,000 m^2 ha^{-1}, indicating the high photosynthetic potential of this variety.

2. The greatest plant height (98.4 cm) at the heading stage was recorded in the variety Uliublena at a seeding rate of 5,500,000 seeds ha^{-1}, whereas the lowest height (73.4 cm) was observed in Grenny at a seeding rate of 4,500,000 seeds ha^{-1}. These results confirm genetically determined differences in morphological traits and varying levels of adaptive responses of varieties to changes in crop density.

3. Maximum fresh vegetative biomass accumulation occurred at the milk ripeness stage. The highest value (2.90 kg m^{-2}) was obtained in the variety Shirokko at a seeding rate of 5,500,000 seeds ha^{-1}, indicating its greater ability to form a powerful assimilatory apparatus and efficiently utilize environmental resources.

4. The highest grain yield was achieved by the variety Shirokko, which increased yield from 5.47 to 5.63 t ha^{-1} when the seeding rate was increased from 4,500,000 to 5,500,000 seeds ha^{-1}. This confirms the high adaptability of the variety to increased plant density and its efficient realization of productivity potential.

5. Technological grain quality indicators were also largely determined by variety and seeding rate. The highest gluten content (30.42%) and protein content (15.64%) were formed by the variety Shirokko at a seeding rate of 5,500,000 seeds ha^{-1}, whereas the lowest protein content (13.41–13.74%) was characteristic of the variety Grenny. This demonstrates the superiority of Shirokko in producing high-quality food-grade grain.

6. The practical significance of the study lies in the fact that, under the conditions of the experiment, the most effective cultivation strategy was the use of the variety Shirokko with a seeding rate of 5,500,000 seeds ha^{-1}, as this combination ensured optimal leaf area development, maximum biomass accumulation, the highest grain yield, and improved grain quality indicators. The obtained results may be used for the improvement of varietal cultivation practices, optimization of seeding rates, and enhancement of the economic efficiency of spring wheat production.

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