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ORIGINAL PAPER

Effect of phosphorus fertilization on technological and geometric grain properties of winter wheat grown in Poland*

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Abstract

The aim of wheat cultivation is to achieve high grain yield while ensuring food quality and adopting environmentally sustainable practices, including the use of alternative phosphorus fertilizers. Grain size and shape are critical parameters influencing technological and industrial processing. This study aimed to evaluate the effects of two phosphorus fertilizers – struvite and superphosphate – on the yield and geometric traits of two winter wheat (*Triticum aestivum* L.) cultivars, Activus and Chevignon, under field conditions. The results demonstrated significant differences between cultivars in grain physical characteristics, including grain density and the proportion of grains >2.5 mm, with Activus exhibiting more favorable traits. Grain width, thickness, and dimension ratios varied significantly depending on both the cultivar and fertilization method. Activus showed higher values of thickness and kernel width index (Kw) under superphosphate fertilization. Conversely, Chevignon exhibited greater grain width, particularly under superphosphate treatment. The cultivar type significantly influenced key geometric parameters, including arithmetic (Da), geometric (Dg), and equivalent (Dp) mean diameters, aspect ratio (Ra), and ellipsoid shape factor (Fz), with higher values observed for Chevignon. Phosphorus fertilization, particularly with superphosphate, positively affected Dg, Dp, Φ, and Ra, suggesting greater effectiveness in enhancing grain morphology. Struvite fertilization resulted in an increase in grain thickness and the sphericity coefficient compared to the control treatment. At the same time, struvite application led to a reduction of the Ra index relative to the control, accompanied by a slight increase in grain volume. Struvite fertilization did not have a significant effect on wheat grain color, therefore further research is needed to examine this trait in an expanded analysis.

Keywords: winter wheat, cultivar, phosphorus fertilization, struvite, grain geometry, technological and physical properties

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INTRODUCTION

In recent years, Polish agriculture has been dominated by the cultivation of cereals, which in some parts of the country occupy more than 70% of arable land. Among this group of crops, wheat has an important role as the primary bread cereal (KOWR 2020, Różewicz 2021). Wheat is a crucial crop that sustains approximately 35% of the world's population. Known for its high nutritional value, ease of storage, and versatility in food production, cereal is a vital food and feed resource. The global demand for wheat is increasing more rapidly than for other major crops. However, with limited arable land, boosting wheat production relies heavily on achieving higher yields. This goal necessitates collaboration among agricultural scientists from various fields, alongside sustained investments and the adoption of innovative agronomic and management practices to maximize production potential (Ali et al. 2020). The modern grain industry requires raw material with high technological value. One of the key factors influencing this quality is grain uniformity, achieved through the maximum alignment of its length, width, and thickness. Grain size and shape (expressed as weight of thousand grain weight (TGW) and grain size distribution of kernels) are traditionally used in the initial assessment of grain quality.

The use value of wheat grain is the result of the genotype, habitat conditions and the agrotechnology used. In the case of wheat, the main role in shaping of this value is attributed to fertilization, especially in interaction with the appropriate amount and distribution of precipitation during the growing season (Lollato et al. 2019, Ballagh et al. 2025). Phosphorus is a crucial nutrient for wheat, contributing significantly to yield improvements (Yan et al. 2025). Wheat varieties with high yield potential require adequate nutrient supply, including phosphorus, to achieve optimal grain production (Makhdum et al. 2024). Struvite (magnesium ammonium phosphate, $MgN_4PO_4 \cdot 6H_2O$) is an innovative and sustainable fertilizer gaining attention in modern agriculture. It is a slow-release phosphorus source, providing essential nutrients like magnesium, nitrogen, and phosphorus, which are critical for plant growth. Struvite is often recovered as a by-product from wastewater treatment processes, offering a circular economy solution by recycling nutrients from waste streams. Its use in agriculture not only reduces dependency on finite phosphate rock reserves but also supports sustainable farming practices by improving nutrient efficiency and reducing environmental impact (Jama-Rodzeńska, Gałka 2022). Research suggests that struvite is particularly effective in crops with a high phosphorus demand, including cereals like lettuce, maize, Sudan grass and rice (Bonvin et al. 2015, Reza et al. 2019, Wen et al. 2019, Sun et al. 2024, Ramut et al. 2025).

This study investigates the impact of various phosphorus fertilization treatments on the geometric traits of wheat (*Triticum aestivum* L.) grain, its colour and the correlation between the geometric traits and chemical composition. Scientific literature devotes much attention to the nitrogen fertilization of quality wheat and its impact on grain yield and technological value (Klikocka et al. 2016). The following study highlights the effect of struvite fertilization on technological and physical characteristics of winter wheat grain as compared to superphosphate fertilization. There are few studies on the evaluation of the physical properties of grain, but none includes the question of the application of struvite. To the best of our knowledge, this is the first study conducted on the agrophysics of grains from wheat plants fertilized with struvite, in which these traits were correlated with grain chemical composition, potentially influencing its industrial quality. The identified traits can be used both for assessing the quality of grain yield and in the process of separating the post-threshing mixture into its constituent fractions, depending on the cultivation method being considered. This study specifically focused on novel wheat cultivars, examining parameters such as grain size, shape, and weight, which have not been extensively explored in previous research. These characteristics are known to impact flour extraction rates, milling efficiency, animal feeding and overall product quality.

The aim of the study was to determine the range of variation in the physical and technological properties of individual grains of wheat. This goal was achieved by thoroughly analyzing the values of these traits of two winter wheat cultivars, Chevignon and Activus, of which Chevignon, but not Activus, is characterized by the Research Centre for Cultivar Testing (COBORU). However, both these cultivars could be considered for inclusion in the COBORU register in the light of our research findings, which provide additional information about the geometric traits of wheat grains, enabling further studies in agrophysics. The aim of the present study was to compare the effects of superphosphate and struvite fertilization on selected physical properties and the technological quality of wheat grain.

MATERIALS AND METHODS

Experiment design and examined factors

The research material consisted of winter wheat grain of the cultivar Activus and Chevignon from a field experiment conducted in 2022-2023 at the Swojec Experimental Farm belonging to the Wroclaw University of Environmental and Life Sciences. The experimental factors were winter wheat cultivars and varied phosphorus fertilization. For the experimental factors and factor levels see Table 1. The field experiment was set up using the split-plot method, in four replicates. The area of a single plot was 15 m² (1.5 m × 10 m).

The previous crop before winter wheat was winter rapeseed. Afterward, ploughing was done to remove the crop residue and reduce weed growth

Table 1

The factors used in the experiment

	Examined factor	Factor level
A	Cultivar	Activus
		Chevignon
B	Phosphorus fertilization	control (the control plot did not receive superphosphate or struvite and was fertilized with nitrogen and potassium only)
		Superphosphate (SUP)
		Struvite (STR)

and water loss. The soil was ploughed in the second week of September. Due to the heavy soil clumping, pre-sowing tillage was performed two days apart using a harrow coupled with finishing rollers and a cultivator with a string roller. Winter wheat cultivars Activus and Chevignon were sown on 20 October 2022, with 260 germinable seeds m^{-2} at a row spacing of 12.5 cm and a sowing depth of 3 cm.

A few days before sowing, phosphorus and potassium fertilization was carried out. Potassium fertilization was carried out at a single dose of 83 kg K ha^{-1}, and the corresponding phosphorus fertilizer (triple superphosphate or struvite) was applied to individual plots at a dose of 39.24 kg P ha^{-1}. Both fertilizers were applied by hand. Struvite, also known as Crystal Green, is an alternative fertilizer (2024). It is pure phosphorus fertilizer available in the form of spherical granules of various sizes. Crystal Green granules are 2.4 mm in diameter (SGN 240, size guide numbers) and contain 5% nitrogen (N), 12.2% P and 10% magnesium (Mg). The fertilizer is manufactured by Ostara (North Warson Rd, Suite) and has low solubility, according to the manufacturer.

Nitrogen fertilization was applied at two doses: 40 kg N ha^{-1} at the first date (tillering and stem elongation, BBCH 24-37) – 25 March 2023 and 60 kg N ha^{-1} at the second date (booting, BBCH 45) – 14 April 2023.

After plant emergence in the second ten days of November, a comprehensive herbicide treatment with Trinity 590 S.C. was carried out to control monocotyledonous and dicotyledonous weeds. In the first ten days of April, a fungicide treatment was carried out with AsPik EC at a dose of 0.9 l ha^{-1}. Ten days later, a wheat canopy regulation treatment was carried out with CCC750 SL at a dose of 1.5 l. Harvesting with a small plot combine harvester was carried out on 10 July 2023.

Two winter wheat cultivars were used in the experiment:

– **Activus**: A winter wheat of the A quality class, bred by Saatbau Linz GmbH (Austria). It is characterized by very high yield, early maturity, but also high protein content. Plants have excellent resistance to fusarium diseases and yellow rust. This wheat cultivar, due to its strong tillering capacity, competes well with weeds and is well suited to delayed sowing dates. Its awned morphology makes it particularly suitable for cultivation in areas subject to high wildlife pressure. The cultivar is also tolerant to periodic water shortages, which enables it to grow on weaker sites (Saatbau 2022).

– **Chevignon**: A winter wheat of quality class A, sourced from the breeding company Saatbau Linz GmbH (Austria). It is characterized by excellent yield potential and good grain quality. It is particularly recommended for cultivation on farms focused on intensive production and achieving the highest yields. It is characterized by good resistance to the most important wheat diseases, which gives the effect of intense greenness from the early stages of development. Suitable for cultivation throughout the country, it is less tolerant of weaker sites where there are periodic water shortages. It is also suitable for sowing at late dates (Saatbau 2022).

Soil conditions

The field experiment was established on shallow Holocene fluvial loams, sedimented on Pleistocene ground moraine and glaciofluvial sands. According to FAO-WRB classification (IUSS Working Group WRB 2022), the soils are classified as Gleyic Fluvic Phaeozems due to the presence of thick mollic horizon and redoximorphic features present in the subsoil. In the Polish soil taxonomy (Kabała et al. 2019), the soil is classified as Mada czarnoziemna (Chernozemic alluvial soil) that primarily resembles the alluvial origins of soil parent material. According to soil-agricultural evaluation, this soil belongs to the quality class IIIb (on a 9-level scale), which means it is evaluated as good and fertile soil, appropriate for wheat cultivation.

Weather conditions

The Selyaninov hydrothermal coefficient (HTC) was used to describe the effect of weather conditions on the development of winter wheat, using the following formula:

$$HTC = \frac{\sum P > 10°C}{0.1 \cdot \sum T)},$$

where: *HTC* – Selyaninov hydrothermal coefficient, *P* – the sum of precipitation in months from April to October, and *T* – the sum of average daily temperatures in each month (Staugaitis et al. 2016). Weather conditions can be categorized based on the *HTC*, which correlates temperature and precipitation levels over a specific period (usually a month). These conditions are classified as: extremely dry (≤0.4), very dry (0.4-0.7), dry (0.7-1.0), somewhat dry (1.0-1.3), optimal

(1.3-1.6), somewhat wet (1.6-2.0), wet (2.0-2.5), very wet (2.5-3.0), and extremely wet (>3.0). Although classification ranges may vary slightly, it is widely accepted that the optimal HTC values are between 1.0 and 1.5 (Dirse, Taparauskiene 2010, Taparauskiene, Miseckaite 2017).

The warm and very dry October was not ideal for sowing winter wheat, but September, the previous month, had 64% higher precipitation than the long-term average, which provided sufficient water resources for plant emergence in October (Table 2). Temperatures and precipitation in March and

Table 2

Weather conditions in the years of the experiment with struvite and winter wheat (2022-2023)

Month	Temperature (°C)			Rainfalls (mm)			Selyaninov's coefficient (HTC)	
	2022	2023	mean 1990-2020	2022	2023	mean 1990-2020	2022	2023
April	6.4	8.1	9.6	32.7	31.8	32.8	1.46	1.31
May	12.7	13.2	14.3	20.9	23.9	58.9	0.44	0.60
June	20.1	18.7	17.8	39.7	73.4	74.6	0.58	2.09
July	20.7	20.7	19.7	132.5	50.5	86.6	2.12	0.79
August	17.7	19.9	19.2	92.5	144.1	63.6	1.45	2.33
September	14.8	17.0	14.2	82.0	4.7	50.6	2.12	0.92
October	9.1	12.0	9.3	8.6	30.0	40.8	0.25	0.81
Mean/sum (April-Oct)	14.5	15.7	14.5	408.9	358.4	377.0	–	–

April were similar to the multi-year period, which created favourable conditions for the proper resumption of spring vegetation. In May, precipitation was lower than the optimum level reported in the literature, which may have positively influenced wheat development during the stalk shooting stage (Woźniak 2019) – Table 2.

At the end of the growing season of winter wheat, weather conditions were not completely in line with the optimal water requirements of wheat, but the differences were not significant, which ensured sufficient water conditions. In addition, temperatures in June and July were only slightly higher than the average values from 1990-2020 (by 0.9°C in each month). In our study, the HTC values suggested that the weather was from very dry to wet in 2022 and from very dry to wet in 2023.

Methods used in determination of the geometric and technological traits of winter wheat

Physical properties of winter wheat

Moisture content

Before the actual analyses were performed, moisture content was determined in wheat grains (PN-ISO 712:2002) and the water content was standardized.

Bulk density

The bulk density of winter wheat grain was determined using a density analyzer in accordance with the PN-ISO 7971-2 standard.

Different fractions of winter wheat grain

The quality parameters in the grain were determined: grain division into fractions using a mechanical sorter (Sadkiewicz Institute, Bydgoszcz) with the following parameters: dimensions – 200 × 520 × 320 mm, weight – 20 kg, sieve length – 430 mm, length of the sieve with frame – 470 mm, sieve width – 150 mm, width of the sieve with frame – 180 mm, thickness of the sieve sheet – 1.3 mm, width of sieve, edges from 4.0 to 6.0 mm, frequency – approx. 310 vibrations min^{-1}, duration of 1 cycle (sorting) – 3 minutes, and the sorter performing horizontal back-and-forth movements. The analysis was performed in accordance with the Polish Standard PN-R-74110:1998. The test method consists of scattering 100 g of winter wheat grains on the surface of the upper sieve and then automatically switching off the device and weighing the separated fractions wheat grain. The dimensions of the sieves (from top to bottom) are 2.8 × 25 mm, 2.5 mm × 25 mm, and 2.2 mm × 25 mm, dividing the seeds into the fractions of >2.8 mm, 2.5-2.8 mm, 2.2-2.5 mm and <2.2 mm. The share of the fractions is expressed in percent.

Technological properties of winter wheat

The weight of thousands grain weight (TGW)

Characteristics of wheat grain comprised the thousand-grain weight. This trait of each grain sample was measured by counting 1000 randomly sampled grains (in six repetitions) and weighing them on an electronic balance with a precision of 0.001 g. Determination of TGW was carried out using a grain counter from the Sadkiewicz Institute (Bydgoszcz, Poland), The thousand grain weight was determined according to Polish Standard No. PN-68/R-74017.

Wheat grain geometry

The physical properties of wheat grains, including grain size, were assessed on 100 grains randomly selected from each sample (in triplicate) and their three linear dimensions, namely length (L), width (W), and thickness (T), were measured using a digital micrometer over three replications, with an accuracy of 0.01 mm.[2] (MIER-MIKR25 micrometer, micrometer screw gauge, Kraków Poland range 0-25mm).

The arithmetic mean diameter (Da), geometric mean diameter (Dg), equivalent mean diameter (D_P), and sphericity (ϕ, respectively, of the grain samples were computed using the following equations (Andersa, 2023):

$$Da = \frac{(L + W + T)}{3} \text{ (mm)},$$

$$Dg = (LWT)^{\frac{1}{3}} \text{ (mm)},$$

$$D_P = [L\frac{(W+T)^2}{4}]^{\frac{1}{3}} \text{ (mm)},$$

$$\phi = \frac{(LWT)^{\frac{1}{3}}}{L} 100 \text{ (\%)}.$$

The overall shape of the grain was determined by the aspect ratio (*Ra*) according to the method of Falade and Christopher (2015) and Markowski et al. (2013):

$$Ra = \frac{W}{L} \cdot 100 \text{ (\%)}.$$

The shape of a grain of wheat can be roughly compared to the shape of a rotating ellipsoid. The ellipsoid shape factor of the analyzed winter wheat grains was calculated using the following formula (Horabik, Molenda 2002, Gierz et al. 2022, Ramaj et al. 2024):

$$Fz = \pi L \frac{T+W}{2} \text{ (mm}^2\text{)}.$$

An indicator of the proportion of dimensions (*Kw*) was calculated according to the following formula (Horabik, Molenda 2002, Gierz et al. 2022, Ramaj et al. 2024):

$$Kw = \frac{T}{L}.$$

The m_D is the specific grain weight (Kaliniewicz et al. 2013):

$$m_D = \frac{m}{Dg} \text{ (g m}^{-1}\text{)},$$

where: m – the grain weight (mg).

The volume of grain (V_g), whose shape resembles a rotational ellipsoid, was also calculated, (Gastón et al. 2002):

$$V_g = \frac{\Pi\, T\, W\, L}{6} \text{ (mm}^3\text{)}.$$

Dholakia et al. (2003) proposed an interesting factor-form-density (FFD) for phenotypic measurements of wheat grain based on the differences in the grain structure (density) and the deviation from the cylindrical form, which was expressed as:

$$FFD = \frac{grain\ weight}{grain\ length \cdot grain\ width}\ [\mathrm{mg\ (mm^2)^{-1}}].$$

Wheat grain colour

The grain colour measurements were made with a Minolta chromameter (using Konica Minolta CM-600d, Sensing Americas). The L* (lightness), a* (redness), and b* (yellowness) values were measured in a Petri dish (90 mm diameter) to a depth of approximately 2 cm prior to colour measurements. Measurements were taken from three different locations on the outer surface of each wheat sample to ensure representativeness. The Munsell system continues to be recognized as an international standard for describing and classifying soil colours. The Munsell system is used to determine diagnostic horizons, characteristics, and materials, and to categorize soils into their appropriate taxonomy units (Kawalko et al. 2023). Hue readings were rounded to the nearest hue on the Munsell charts, typically to 10YR or 2.5Y. The grain colour in our study was analyzed using the CIE 1976 L*, a*, b* colour space, with measurements performed using a MINOLTA CR-300 tristimulus colorimeter. The colour of a representative grain sample is a parameter difficult to define unambiguously using simple sensory methods due to the heterogeneity of samples and the presence of slight colour deviations.

Statistical analysis

Statistical analysis and visualization were performed using Statistica version 13.3 (TIBCO Software Inc., 2024) and R Statistical Software (v4.1.2; R Core Team 2021). The results of the study were statistically processed using analysis of variance in Statistica programme. The normal distribution of the traits studied was tested using the Shapiro-Wilk test. If the traits did not follow normal distribution, non-parametric tests were performed. In the case of a distribution other than normal, the non-parametric *U* Mann-Whitney test was used for analysis. Homogeneous groups were distinguished using a post hoc test in the case of normal distribution and Anova if normal distribution was not determined.

RESULTS AND DISCUSSION

The cultivar Activus had a higher bulk density and a higher share in the largest fraction (fraction 2.8) while cv. Chevignon had a higher share in the medium and smallest fraction (fractions 2.5 and 2.2 mm) – Table 3. Grain weight is a key factor influencing overall yield in crops such as wheat. A larger grain weight generally leads to a higher total yield, as each individual grain is heavier. There were no statistical differences in TGW and grain moisture between the cultivars or between different phosphorus fertilization regimes. The only interaction between the examined factors concerned

Table 3

The effect of struvite on grain parameters of winter wheat cultivars (mean and standard error)

Factors of the experiment	Bulk density	Fraction of grain				Technological properties	
		>2.8 mm	2.5-2.8 mm	2.2-2.5 mm	<2.2 mm	TGW	Grain moisture
	(kg hl^{-1})	(%)				(g)	(%)
Cultivar (A)							
Activus	80.57^{b}±0.43	65.57^{b}±60.68	18.68^{a}±0.57	6.25^{a}±0.42	9.53±0.27	48.06±0.58	10.75±0.13
Chevi-gnon	77.35^{a}±0.43	55.13^{a}±0.68	25.16^{b}±0.57	11.04^{b}±0.42	9.05±0.27	47.10±0.58	10.60±0.13
p-value	***	***	**	**	ns	ns	ns
Phosphorus fertilization (B)							
Control	78.60±2.48	60.00±2.48	20.56±1.61	9.60±1.15	9.38±0.30	9.18±0.72	10.86±0.19
SUP	78.83±2.48	60.71±2.48	19.45±1.61	8.56±1.15	8.71±0.30	9.22±0.72	10.51±0.19
STR	79.56±2.48	60.35±2.48	20.21±1.61	7.78±1.15	9.78±0.30	9.30±0.72	10.65±0.19
p-value	ns	ns	ns	ns	ns	ns	ns
A × B	ns	ns	ns	**	ns	ns	ns

SUP – superphosphate, STR – struvite, TGW – thousand grain weight (g), Means for factors within a column marked with the same letter do not differ significantly. Significance levels: not significant (ns), p<0.01 (**), p<0.001 (***).

the smallest fraction (2.2 mm) of grain. The interaction of examined factors showed that the share of lowest fraction 2.2 on the total was significantly lower in Activus compared to Chevignon in all treatmenst (Figure 1). The 2.2 mm fraction of cv. Chevignon in the control was significantly higher compared to other combinations, whereas cv. Activus the lowest showed

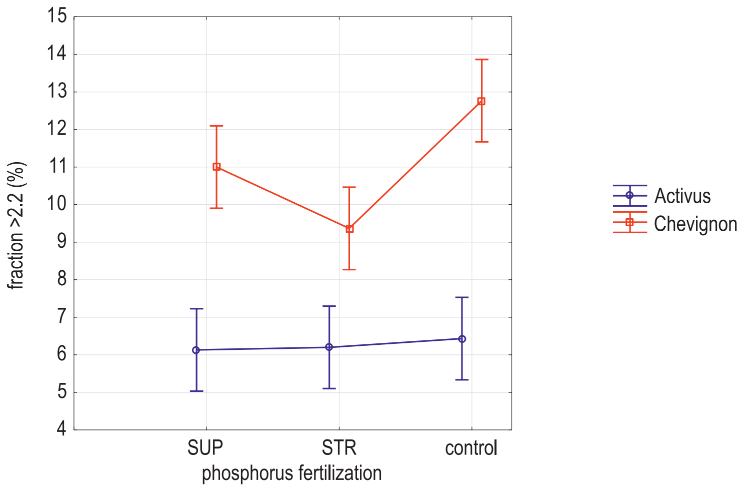


Fig. 1. Interaction of examined factors and its effect on the 2.2 mm fraction of winter wheat grain

no differences between treatments. Phosphorus fertilization had no impact on the mentioned fractions and technological properties.

There were both negative and positive correlations between different size fractions of winter wheat grains. Negative correlations were observed between the 2.5 mm and 2.8 mm fractions, as well as between the 2.2 mm and 2.8 mm fractions. In contrast, a positive correlation was found between the 2.2 mm and 2.5 mm fractions (Table 4).

Table 4

Spearman's correlation between fractions of wheat grain (n=18)

Variable	2.5-2.8 (mm)	2.2-2.5 (mm)	<2.2 (mm)
>2.8 (mm)	-0.96**	-0.91**	0.30
2.5-2.8 (mm)		0.83**	-0.32
2.2-2.5 (mm)			-0.40

The strength of correlation was classified according to the following criteria: $|r|$ = ** 0.80-1.00 – very strong.

There was no significant effect of the experimental factors studied on wheat grain length. It was found that the grains of cv. Chevignon were significantly wider compared to those of cv. Activus. This means that the Chevignon grains have a larger diameter or span compared to those of the Activus grains. On the other hand, the width, thickness and Kw significantly differed according to the cultivar and fertilization. Higher thickness and Kw values were found in cv. Activus. Fertilization with superphosphate had the strongest effect on width, thickness, and Kw (Table 5). Width as well thickness

Table 5

Comparison of the physical properties of grains of two wheat cultivars depending on fertilization

Specification	Wheat grain geometry					
	L	W	T	Kw	weight	FFD
	(mm)			(ratio)	(mg)	mg $(mm^2)^{-1}$
Cultivar (A)						
Activius	6.26±0.02	3.36^a±0.01	2.96^a±0.01	0.47^a±0.002	49.81±0.48	2.39^a±0.03
Chevignon	6.26±0.02	3.56^b±0.01	2.84^b±0.01	0.46^b±0.002	48.78±0.48	2.22^b±0.03
p-value	ns	***	***	**	ns	***
Phosphorus fertilization (B)						
Control	6.25±0.02	3.43^a±0.01	2.87^a±0.01	0.46^a±0.002	49.45±0.48	2.33±0.03
SUP	6.26±0.02	3.50^b±0.01	2.93^b±0.01	0.47^b±0.002	49.17±0.48	2.29±0.03
STR	6.26±0.02	3.44^a±0.01	2.90^b±0.01	0.46^a±0.002	48.96±0.48	2.30±0.03
p-value	ns	*	*	*	ns	ns

L – grain length, W – grain width, T – grain thickness, Kw – indicator of the proportion of dimensions, FFD – factor-form-density; Significance levels: not significant (ns), p<0.05 (***), p<0.01 (**), p<0.001 (***).

achieved higher values compared to control plots. The application of superphosphate led to the wheat grain attaining higher Kw values compared to the other treatments. The FFD trait was significantly higher for the Activus cultivar, but fertilization had no effect on this parameter. The experimental factors had no significant effect on the weight of grain (Table 5).

Grain length of cv. Chevignon grains was higher compared to that of cv. Activus grains. Conversely, for cv. Activus, longer grains were observed in the control (Figure 2). In the case of grain width, higher values were

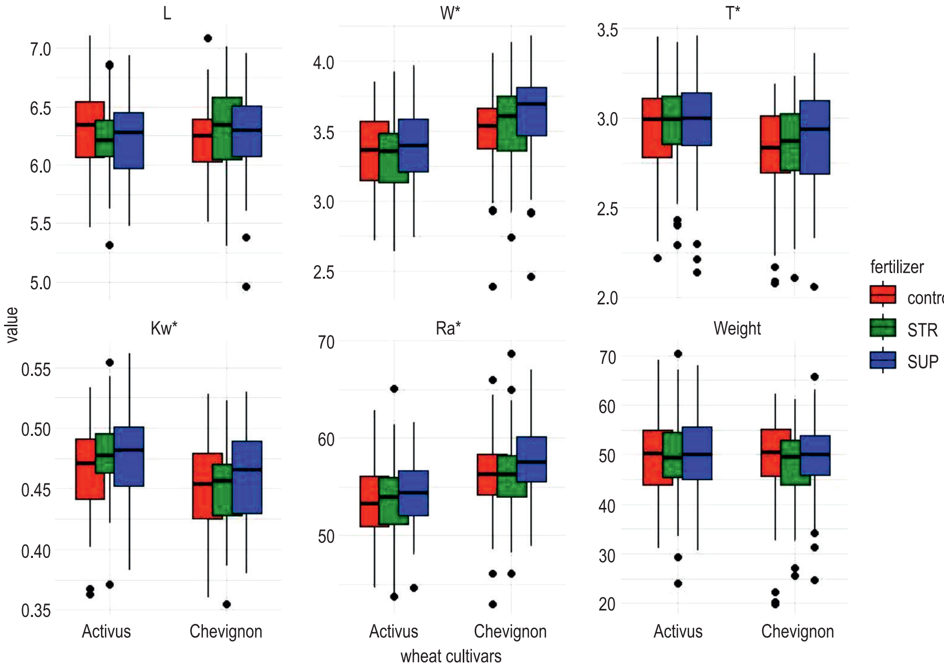


Fig. 2. Interaction effect of phosphorus fertilization and cultivar on geometric dimensions and indicators of two winter wheat cultivars

obtained for cv. Chevignon in all tested combinations than for cv. Activus. The application of superphosphate to cv. Chevignon was more beneficial compared to cv. Activus. As for grain thickness, cv. Chevignon fertilized with superphosphate produced the thickest grains, while the values of this parameter for cv. Activus grain were similar across all treatments. Phosphorus fertilization applied to cv. Activus did not increase grain thickness compared to the control. Superphosphate applied to cv. Chevignon caused higher Kw values compared to those determined for cv. Activus. The lowest Kw value was observed in the struvite treatment applied to cv. Activus. Statistically higher values of Ra were observed in cv. Chevignon in all treatments compared to cv. Activus. With respect to weight, struvite fertilization resulted in the lowest values in cv. Chevignon compared to cv. Activus.

In cv. Chevignon, the highest values were observed under control treatments compared to SUP and STR.

The correlations between the examined grain dimensions were analyzed, revealing both positive and negative relationships between different measurements. These correlations provide insight into how changes in one dimension (e.g., length, width, thickness) might influence the others; they can also help identify patterns in grain development under different treatments or in different varieties (Table 6). Length had positive correlations with thickness, width of the grain and indicators like Da, Dg, Dp, Fz, and negative correlations with Φ and Kw. Thickness correlated positively with length, width, Da, Dg, Dp, Φ, Fz and Kw. Generally, all parameters demonstrated positive correlations with one another. Negative correlations were only observed in the case of Φ and Kw versus the length of grains.

Table 6

Correlations between the examined grain dimensions (n=18)

Variable	T	W	Da	Dg	Dp	ϕ	Fz	Kw
L	0.43	0.55	0.85**	0.74*	0.74*	-0.13	0.83**	-0.17
T		0.49	0.73*	0.81**	0.78*	0.66*	0.72*	0.78*
W			0.83**	0.84**	0.87**	0.56	0.83**	0.20
Da				0.98**	0.98**	0.36	0.99**	0.24
Dg					0.99**	0.52	0.98**	0.39
Dp						0.53	0.98**	0.36
ϕ							0.37	0.85**
Fz								0.24

L – grain length, W – grain width, T – grain thickness, Kw – indicator of the proportion of dimensions, FFD – factor-form-density. The strength of correlation was classified according to the following criteria r=0.00-0.19 – very weak, 0.20-0.39 – weak, 0.40-0.59 – moderate, * 0.60-0.79 – strong; ** 0.80-1.00 – very strong.

Grain length (L) ranged from 5.5 mm to 7.1 mm (Figure 3). The most common L was 6.4 mm (which appeared in approximately 15% of cv. Activus grain and 14% of cv. Chevignon grain) and 6.1 mm (ca. 12% of grain from both cultivars Activus and Chevignon) (Figure 5). The lowest percentage was observed for the smallest fractions, below 5.5 mm, in both cultivars (although more numerously in cv. Chevignon), followed by the lengths of 7 and 7.1 mm. More grains with the length of 5.5 mm were obtained from cv. Activus, while grains with 5.6 mm L were more numerous in cv. Chevignon grain. The cultivar Activus had a higher percentage of grains in the 5.7 mm L fraction, while grains with the length of 5.8 mm made up the same percentage among the grains from both cultivars. A higher percentage (about 10%) was noted for grains with L of 5.9 and 6 mm. The cultivar Activius had a higher share of grain with L 5.9 mm and cv. Chevignon had a higher share of grains with L 6.0 mm (Figures 3-5).

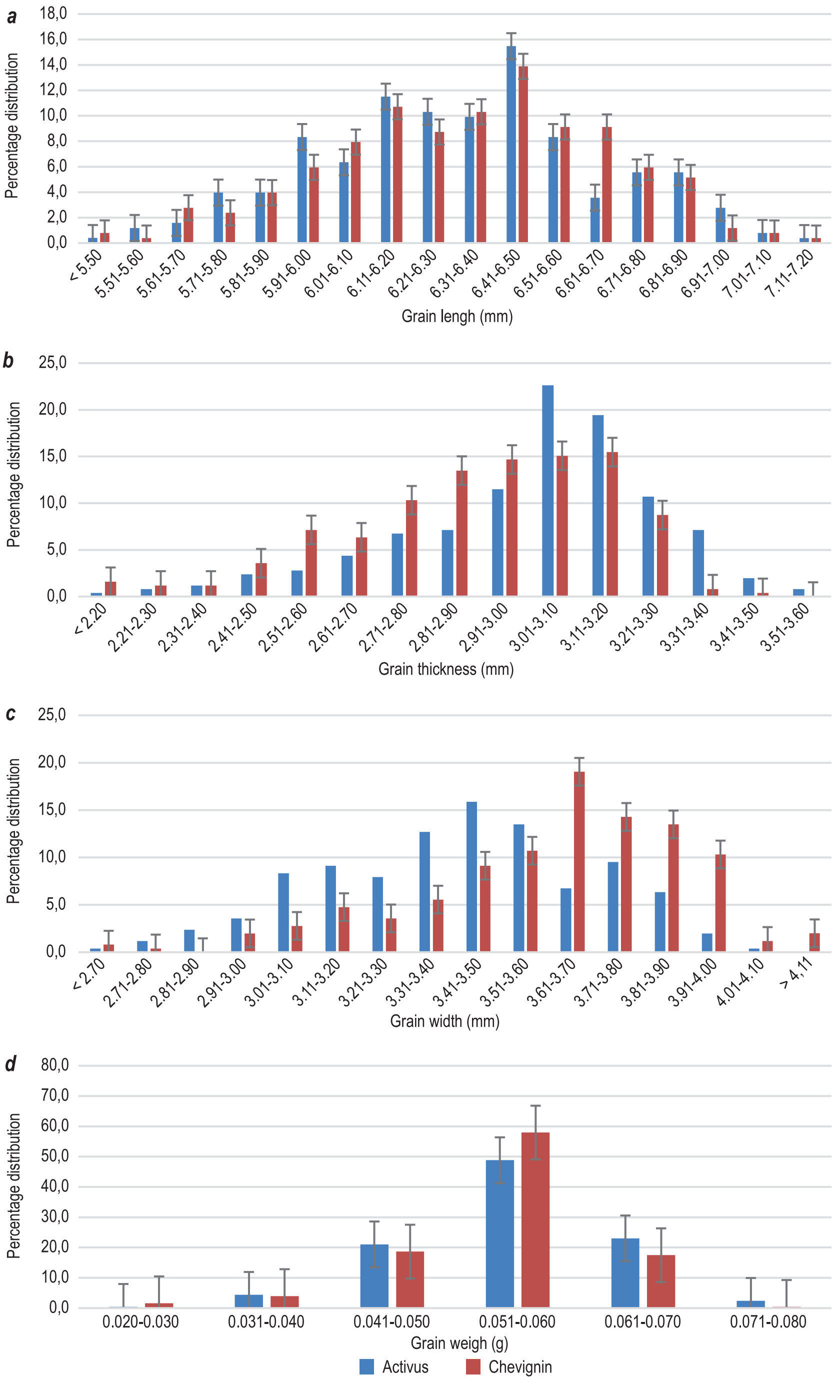


Fig. 3. Percentage distribution of: *a* – grain length (L), *b* – grain thickness (T), *c* – grain width (W), *d* – grain weight

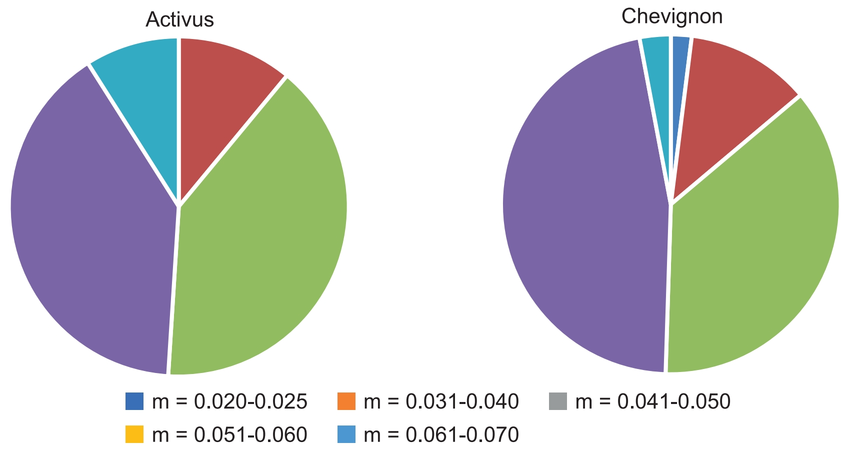


Fig. 4. Frequency of occurrence (%) in the determined mass ranges (g)

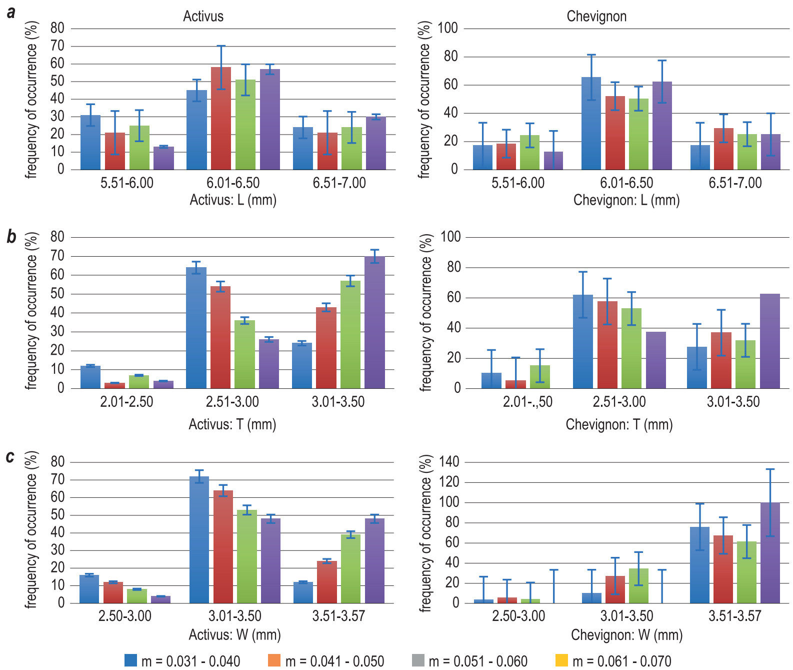
The distribution of grain thickness (T) differed between the cultivars (Figures 3-5). The range of T was from 2.1 mm to 3.4 mm for cv. Chevignon and from 2.1 to 3.5 mm for cv. Activus (Figure 3). The highest percentage of grains according to the thickness (T) was made up of cv. Activus kernels 3.0, 3.1, and 3.2 mm thick. Cv. Chevignon dominated within the T classes of 2.4, 2.5, 2.6, 2.7, 2.8, and 2.9 mm, reaching the maximum percentage of 15%. However, there were no grains of cv. Chevignon in the last thickness group (3.5 mm) – Figure 5.

The grain width (W) distribution started from 2.7 mm up to 4 mm for cv. Activus and even above 4 mm for cv. Chevignon (Figure 3). The highest percentage of about 18% corresponded to the W of 3.6 mm, which prevailed in cv. Chevignon. Larger widths, specifically 3.7 mm, 3.8 mm, and 3.9 mm, had frequencies that did not exceed 14% (Figure 5). Grains with a width higher than 4 mm were not observed for cv. Activus.

The highest percentage of wheat grain weight, equal to 60%, was in the range of 0.05 g. The lowest percentage, less than 10%, was determined for grains with a mass of 0.02 g (found only in cv. Chevignon) and 0.07 g (found only in cv. Activus) – Figures 3 and 4.

The cultivar differentiated the parameters Da, Dp, Ra and Fz. Higher values of these parameters were found for cv. Chevignon (Table 7). Phosphorus fertilization affected the parameters Dg, Dp, Φ, Ra. Superphosphate fertilization, which also led to higher V values, turned out to be more effective.

No significant correlation was found between the selected geometric dimensions and chemical composition of wheat grain (Table 8). The only correlation between the geometric traits was between thickness and length. There were statistically significant positive relationships between crude protein and true protein, phosphorus and magnesium, as well as between phos-



Frequency between grain mass and grain length (GL), thickness (GT) and width (GW)

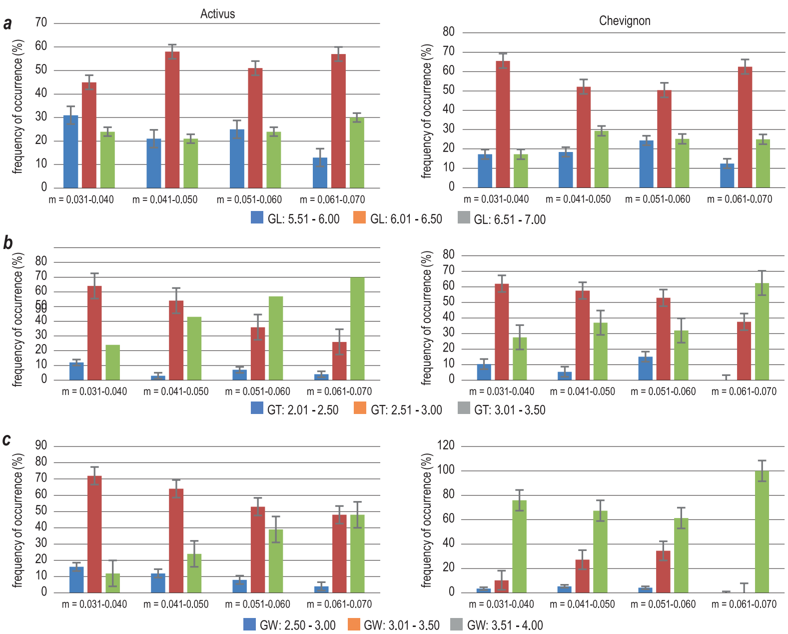


Fig. 5. Percentage distribution of: *a* – grain length (L), *b* – grain thickness (T), *c* – grain width (W)

Table 7

Comparison of the physical properties of two wheat grain cultivars depending on fertilization

	Physical properties							
	Da	Dg	Dp	Φ	Ra	Fz	V	m_D
	(mm)			(%)		(mm^2)	(mm^3)	$(g\ m^{-1})$
Cultivar (A)								
Activus	4.19^{a}±0.01	3.96±0.01	3.96±0.01	63.27±0.02	53.66±0.28	62.19±0.46	32.80±0.38	12.61±0.34
Chevignon	4.22^{b}±0.01	3.98±0.01	4.00±0.01	63.54±0.02	56.91±0.28	63.08±0.46	33.53±0.38	12.30±0.34
p-value	*	ns	*	ns	***	*	ns	ns
Phosphorus fertilization (B)								
Control	4.18±0.01	3.94^{a}±0.01	3.95^{a}±0.01	62.98^{a}±0.02	55.01^{a}±0.28	61.98±0.56	32.61^{a}±0.46	12.57±0.42
Sup	4.23±0.01	4.00^{b}±0.01	4.01^{b}±0.01	63.93^{b}±0.02	55.95^{b}±0.28	63.38±0.56	33.91^{b}±0.46	12.57±0.42
Str	4.20±0.01	3.96^{a}±0.01	3.98^{a}±0.01	63.33^{ab}±0.02	54.93^{ab}±0.28	62.51±0.56	32.98^{ab}±0.46	13.05±0.42
p-value	ns	*	*	*	**	ns	*	ns

Da – arithmetic mean diameter, Dg – geometric mean diameter, Dp – equivalent mean diameter, Φ – sphericity, Ra – aspect ratio, sd – standard deviation, CV – coefficient of variation (= (sd/mean) × 100), significance levels: not significant (ns), $p<0.05$ (*), $p<0.01$ (**), $p<0.001$ (***).

Table 8

Spearman rank order correlation of selected geometric features and chemical composition of wheat grain (n=18)

Variable	TP	CA	P	N	K	Mg	GL	GT	GW
CP	0.79^{*}	0.26	0.49	0.46	0.21	0.56	0.06	0.01	0.44
TP		0.40	0.45	0.30	0.19	0.55	-0.25	-0.16	0.40
CA			0.44	0.12	0.07	0.34	-0.24	-0.28	-0.33
P				0.10	0.46	0.96^{**}	-0.35	-0.23	0.018
N					-0.58	0.16	0.01	0.33	-0.14
K						0.45	-0.12	-0.36	0.34
Mg							-0.41	-0.29	0.11
GL								0.56	0.31
GT									0.00

CP – crude protein, TP – true protein, CA – crude ash, P – phosphorus, N – nitrogen, K – potassium, Mg – magnesium, GL – grain length, GT – grain thickness, GW – grain width. The strength of correlation was classified according to the following criteria: $|r| = {}^{*}$ 0.60-0.79 – strong, ** 0.80-1.00 – very strong. The values of those macroelements were analysed and presented in the manuscript by Szuba-Trznadel et al. 2024.

phorus and crude protein. There were also positive relationships between crude protein and magnesium, and between protein and magnesium. There was also a synergistic effect between P and Mg.

A negative correlation was found between the copper (Cu) content and the grain thickness (GT), m_D, and V (which means that as the parameters GT, m_D and V increase, the Cu content decreases). Additionally, a positive correlation was observed between copper and the grain width (GW), where the Cu content coincided with a greater GW. A positive correlation was also found between FFD and the zinc (Zn) content in grain, as well as between manganese (Mn) and m_D (Table 9).

Table 9

Rank order correlation of selected geometric features and micronutrients of wheat grain (n=18)

Variable	Cu	Zn	Mn
L	-0.26	-0.32	-0.30
T	-0.59	-0.34	0.22
W	0.47	-0.04	-0.26
TGW	-0.19	0.24	0.33
m_D	-0.49	0.18	0.57
V	-0.64*	-0.29	0.22
FFD	-0.12	0.47	0.34

L – grain length, T – grain thickness, W – grain width, TGW – weight of thousand grain weight. The strength of correlation was classified according to the following criteria: $|r|$ = * 0.60-0.79 – strong, ** 0.80-1.00 – very strong. The values of those microelements were analysed and presented in the manuscript by Szuba-Trznadel et al. (2024).

A positive correlation was found between the content of crude protein (CP) and true protein (TP) with total amino acids (AA) and total essential amino acids (EAA). A positive correlation was also observed between TP, predicted protein efficiency ratio (PER2, PER 3) and BV – Table 10. We calculated the following values according to the formulas:

Table 10

Rank order correlation of selected protein and biological value of wheat grain (n=18)

Variable	AA	EAA	Share of EAA in AA	PER 1	PER 2	PER 3	BV
CP	0.63*	0.64*	0.28	0.09	0.09	0.21	0.13
TP	0.87**	0.85**	0.28	0.50	0.46	0.60*	0.47

CP – crude protein, TP – true protein, AA – total amino acids, EAA – total essential amino acids, PER – the predicted protein efficiency ratio, BV – the biological value of the protein. The strength of correlation was classified according to the following criteria: $|r|$ = * 0.60-0.79 – strong, ** 0.80-1.00 – very strong. The values of those parameters were calculated and presented in the manuscript by Szuba-Trznadel et al. 2024.

The results of colour analysis indicated that the surface colour parameters of the grain, including L* (whiteness), a* (redness), and b* (yellowing), varied between the cultivars (Table 11). The a* values represent a colour spectrum from red to green, with positive values indicating a red hue and negative values suggesting a green hue (Yousefian et al. 2021). The b* values correspond to a range from yellow to blue, where positive values denote

Table 11

Colour identification of different groups of grains according to the Munsell scale (mean values for all samples)

Specification	L*	a*	b*	Munsell hue	Munsell value	Munsell chroma
Cultivar (A)						
Activus	60.57	7.54[a]	18.07[a]	8.36YR[b]	5.94	3.18[a]
Chevignon	61.65	9.13[b]	20.10[b]	7.84YR[a]	6.06	3.65[b]
p-value	ns	***	***	***	ns	***
Phosphorus fertilization (B)						
Control	61.61	8.21	18.07*a*	8.14YR	6.05	3.38
SUP	61.60	8.53	19.74	8.11YR	6.05	3.52
STR	60.14	8.26	18.56	8.06YR	5.90	3.33
p-value	ns	ns	ns	ns	ns	ns
A × B	ns	ns	ns	ns	ns	ns

SUP – superphosphate, STR – struvite. L* (whiteness), a* (redness) and b* (yellowing). Means for factors within a column marked with the same letter do not differ statistically significantly. Significance levels: ns – not significant, p<0.001 (***).

a yellow hue and negative values indicate a blue hue. In this study, we observed positive a* values, suggesting a red hue. The average comparison of surface colour parameters of wheat grains under different phosphorus fertilization, as shown in Table 12, revealed that whiteness (L*) remained consistent regardless of the phosphorus fertilization levels. The only differences observed between the cultivars were in a*, b*, and Munsell chroma. The average a* values (redness) for wheat grains ranged from 7.54 (cv. Activus) to 9.13 (cv. Chevignon). Regarding the surface colour scale b* (yellowing), results indicated that the value was higher in cv. Chevignon than in cv. Activus. The average b* values ranged from 18.07 (cv. Activus) to 20.10 (cv. Chevignon). Phosphorus fertilization had no impact on the mentioned traits.

Table 12 showed correlations between the colour parameters (L*, a*, and b*) of wheat grains. The mean and standard deviation values for each parameter are presented, along with their correlation coefficients: L* (whiteness) has weak correlations with a* (redness) and b* (yellowing), with values of 0.06 and 0.26, respectively. a* (redness) is strongly correlated with b* (yellowing) at 0.81*, indicating a significant relationship, while b* (yellowing) has a moderate correlation with L* (0.26) and a strong correlation with a* (0.81*).

Table 13 shows the correlations between Munsell value, chroma, and hue. Munsell value has a strong correlation with Munsell hue (0.74*) and a weaker one with Munsell chroma (0.31*). Chroma and hue are weakly correlated (0.23), with chroma showing a moderate correlation with Munsell

Table 12

Rank order correlation of colour identification (n=48)

Variable	Mean	Standard deviation	a*	b*
L*	61.12	2.02	0.06	0.26
a*	8.33	1.01		0.81*
b*	19.09	1.54		

(L*) whiteness, a* (redness) and b* (yellowing). The strength of correlation was classified according to the following criteria: $|r|$ = * 0.60-0.79 – strong, ** 0.80-1.00 – very strong.

Table 13

Rank order correlation of colour identification according to the Munsell scale (n=48)

Variable	Mean	Standard deviation	Munsell chroma	Munsell hue
Munsell value	6.00	0.20	0.31	0.74*
Munsell chroma	3.41	0.31		0.23
Munsell hue	8.10	0.40		

The strength of correlation was classified according to the following criteria: $|r|$ = * 0.60-0.79 – strong.

value (0.31*). A positive correlation was found between chroma and value, hue and value, value and chroma, as well as value and hue in the Munsell system.

This preliminary study, carried out over a one-year cycle, investigated the application of struvite and its impact on geometric traits and quality of wheat grains. While the scientific literature includes studies on the effects of various phosphorus fertilizers on plant growth and physical traits, no research has directly addressed the influence of struvite on the geometric traits of wheat grains. Although struvite has been explored as an alternative phosphorus source in plant fertilization, its effect on grain parameters such as shape, size, and dimensional ratios remains unstudied. Therefore, this work represents a novel contribution to this topic, offering new insights into the potential benefits of struvite in wheat cultivation. The findings help clarify how struvite may affect grain characteristics such as size, shape, and weight, which are directly linked to crop quality and yield potential. The geometric properties of cereal grains are varietal traits, with the ratio of their dimensions remaining approximately constant, regardless of climatic and soil conditions, as demonstrated in this study (Gierz et al. 2022, Ramaj et al. 2024).

The bulk density of the stored material (grain) is the main factor considered in the design of drying and aeration systems because it is one of the physical properties that affects the resistance to air flow in the stored mass (Gierz et al. 2022, Labrot-Rhodes et al. 2025). Bulk density is constantly changing due to the stresses in the silo and deformation of stored material. Higher grain density indicated that the grain was harvested at its best physiological maturity phase, i.e., full maturity. This property also characterizes the consumption quality of grains (Devi et al. 2022, Różewicz et al. 2024). High wheat grain density (test weight) is associated with well-filled kernels, indicating good milling quality and higher flour extraction rate (Wang, Fu 2020, Lakić-Karalić et al. 2021, Wang et al. 2023). The average bulk density of wheat grain in Poland is reported to be approximately 75.35 kg hl^{-1} (Woźniak, Gontarz 2011), while recent studies confirm that grain quality traits are strongly influenced by agronomic practices and cultivar characteristics (Kang et al. 2026). Similar density values were also reported by Dziura et al. (2017) for wheat grain provided by farmers to agricultural research laboratories. In our study, bulk density depended on the winter wheat cultivar tested, with a higher value determined for cv. Activus (80.57 kg hl^{-1}) than for cv. Chevignon (77.35 kg hl^{-1}).

The TGW is a critical parameter in agricultural research and breeding. It is used to evaluate seed size, which can be an indicator of overall crop quality and productivity (Ahmadi et al. 2024). The kernels of winter wheat (regardless of a cultivar and fertilization level) were larger than those of spring wheat. Grain quality and physical properties of the tested cultivars always depended strongly on the cultivar and above all on the form of winter wheat, while the effect of N fertilization was not consistent. Jańczak-Pieniążek et al. (2020) found that among the physical properties of the winter wheat grains studied, the hybrid cultivar Hypocamp exhibited the highest TGW, while the varieties Hypocamp and Hyvento were characterized by the significantly highest bulk grain density.

In our study, there were no statistical differences between the mentioned traits depending on the cultivars or phosphorus fertilization treatments. Similarly to our findings, Wojtkowiak et al. (2018) determined that the winter wheat grain weight was not affected by the cultivar effect. Ali et al. (2020) reported significant differences in the TGW across different phosphorus treatments. The application of 90 kg P ha^{-1} resulted in the highest TGW (36.45 g), while the control treatment (0 kg P ha^{-1}) produced the lowest TGW (35.22 g). These findings align with those of Alam et al. (2003), who reported significant improvements in TGW with phosphorus application to wheat, an effect that has also been confirmed in more recent studies (Mubeen et al. 2021, Yan et al. 2024). Similarly, by applying phosphorus, the plant's nutrient uptake is improved, leading to better development of the grains, which enhances their weight. This, in turn, contributes to higher yields. Our study supports the observation that phosphorus is a critical nutrient for improving grain size and overall yield in wheat, although it was not depended on the examined factors.

Previous studies have shown that the size and morphology of wheat grains may vary depending on spike architecture and the position of grains within spikelets (Xie et al. 2015, Zhou et al. 2021, Luo et al. 2023). Differences in grain traits along the spike have been reported, with grains located in different spikelets differing in their dimensions, including length and width. According to Wang and Fu (2020), kernel size is also an important trait associated with grain quality and yield components. In our study, no differences were observed between the tested cultivars or phosphorus fertilization treatments with respect to grain length.

A higher Kw index means that the grains of this cultivar may have better quality, such as higher fullness, higher nutritional content, or better germination potential. The Kw index is commonly used to assess grains quality, and its higher value may indicate more valuable grains in terms of usability. In our study, Kw significantly depended on phosphorus fertilization, attaining higher values under superphosphate fertilization. The cultivar Activus was characterized by a higher value of this ratio compared to cv. Chevignon.

Warechowska et al. (2019) reported that the cultivar and climatic conditions had the highest impact on grain weight and grain diameter of wheat. Further, they observed interactions between the cultivar and nitrogen fertilization for grain weight and grain diameter. Of the two varieties used in the study, cv. Parabola wheat grain had a higher weight and diameter.

The colour of wheat grains plays a crucial role in the milling and baking industries, as it influences the colour of the final products. Wheat cultivars with coloured grains can serve as a source of anthocyanins and carotenoids, particularly suited to produce specialty baked goods, primarily those made from whole grains. Instrumental colour measurement is mainly applied to wheat. The relationship between colour characteristics and grain size in different cultivars of wheat has been investigated. The colour of grains is influenced by both genetic and environmental factors. Climatic and soil conditions, diseases (especially fungal infections), pests, and the use of plant protection products may significantly affect grain coloration (Li et al. 2023, Wu et al. 2025). Darkening visible on the ventral side may also result from improper drying processes. Wirkijowska and Rzedzicki (2012) reported that spring barley exhibited considerable variation across subsequent growing seasons in the coloration of both the grain surface and the groove. Similar variability in grain traits influenced by environmental conditions has also been reported in more recent studies on cereals (Filip et al. 2023, Bratković et al. 2024). In this study, only differences between cultivars in a range of a*, b*, Munsell chroma and Munsell colour were observed. The first two parameters were higher for cv. Activus while the latter was higher for cv. Chevignon. In this study, differences between cultivars were observed only for the colour parameters a*, b*, Munsell chroma, and Munsell hue. The values of a*, b*, and Munsell chroma were higher for cv. Chevignon, whereas higher Munsell hue values were recorded for cv. Activus.

The relationship between the content of micronutrients in the grain and its physical dimensions (e.g., size, mass, density) may vary depending on many factors, such as plant species, soil conditions, fertilization, plant genotype, and climatic conditions. The plant genotype can influence both the physical dimensions of the grain and its ability to accumulate micronutrients. Some plant varieties may be more efficient in absorbing and storing micronutrients, which may be independent of the grain size (Hao et al. 2022, Miner et al. 2022).

CONCLUSIONS

The geometric characteristics of grains from wheat cultivars were analyzed to evaluate their influence on grain quality. The results indicated that variation in geometric properties between the cultivars could significantly affect the final quality of wheat, highlighting the importance of selecting cultivars with optimal grain characteristics for improved processing and end-product performance. The study demonstrated that the cultivar had a significant impact on selected geometric traits of the grain, which can serve as a valuable guideline when selecting an appropriate cultivar for specific production purposes. The lack of correlation between the chemical composition and the geometric composition means that geometric traits, such as the size, shape, or thickness of wheat grains, did not have a direct impact on the chemical content of the grain, except for selected micronutrients (Cu, Zn, Mo). This may suggest that the factors influencing the chemical composition of wheat grains are independent of their geometric characteristics. Phosphorus fertilization caused significant changes in geometric features; however, in no case did struvite outperform superphosphate. Struvite did not affect any of the examined geometric properties of winter wheat grains, nor did it deteriorate them. Therefore, its presence did not negatively influence the quality of the grain in terms of these characteristics. Struvite fertilization increased the grain thickness (T) and sphericity (Φ), reduced the Ra index, and slightly increased grain volume compared to the control, while having no significant effect on grain colour. These changes in geometric and surface properties may directly influence grain behaviour during mechanical processing, particularly milling and grinding. The ongoing mechanization of cereal production and processing requires detailed knowledge of the basic physical properties of individual kernels, which determine their resistance to mechanical damage, energy requirements for comminution, and milling efficiency. Changes in grain thickness or shape may therefore affect fragmentation patterns during milling. Consequently, the observed effects of struvite fertilization warrant further investigation to better understand their impact on industrial grain processing.

Author contributions

A.Sz.T. – methodology, A.Sz.T., A.J.R. – conceptualization, B.G., B.F. – data curation, B.G., B.F., Z.K., J.G. – formal analysis, A.J.R. – funding acquisition, A.Sz.T., A.J.R., R.N. – investigation, B.G. – project administration, A.Sz.T., R.N – resources, J.K. software, A.Sz.T. supervision, J.K., A.Sz.T., R.N., A.J.R. – visualization, A.Sz.T., A.J.R., R.N., J.K. writing – original draft preparation, A.Sz.T., R.N. writing – review & editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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