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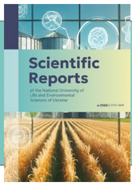

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Formation of maize grain quality indicators under the influence of seeding rates and field productivity zones

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Abstract. Maize grain quality is an important indicator of the effectiveness of agrotechnologies and is shaped by the spatial heterogeneity of soil and climatic conditions and the level of intra-crop competition. The aim of the study was to determine the effect of field productivity zones and variable seeding rates on yield and maize grain quality indicators, in particular test weight, thousand-kernel weight, starch, protein and fat content. Field experiments were conducted during 2023-025 within three field productivity zones (high, medium and low), identified on the basis of long-term yield maps and spatial analysis. The experiment was established using five seeding rates: 65, 70, 75, 80 and 85 thousand seeds per hectare. The results showed that the productivity zone was the dominant factor in the formation of yield and grain quality indicators, while the seeding rate determined the degree to which the potential was realised within each zone. The highest average yield (11.3 t/ha) was obtained in the high-productivity zone at a seeding rate of 80 thousand seeds per hectare, whereas in the low-productivity zone the maximum values did not exceed 7.7 t/ha. Grain test weight and thousand-kernel weight decreased from high to low productivity zones, indicating a deterioration of grain filling conditions under limited resource availability. Starch content was higher in high-productivity zones (up to an average of 72.5%), while medium and low zones showed an increased concentration of protein and fat, reflecting an adaptive response of the crop to stress conditions and reduced yield. The obtained results

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confirm the feasibility of applying zonally differentiated seeding rates as a tool for simultaneous optimisation of maize grain yield and quality

Keywords: *Zea mays* L.; grain quality indicators; test weight; thousand-kernel weight; starch, protein and fat content; variable-rate seeding; productivity zone

Introduction

Under current conditions of climate change and increasing spatial heterogeneity of agricultural landscapes, improving maize (*Zea mays* L.) production technologies with consideration of local soil and environmental field conditions is becoming particularly relevant. Spatial variability of the physical and chemical properties of soil, water regime and nutrient availability leads to the formation of different productivity zones within a single field, resulting not only in differences in yield but also in changes in grain quality indicators. Under such conditions, the application of fixed seeding rates does not allow full realisation of the crop's potential or efficient use of available resources.

Studies by H.M. Salem *et al*. (2024) confirmed that within-field spatial variability of soil properties can be effectively used to delineate management zones based on geostatistical and multivariate analysis methods. The authors showed that field zoning based on a combination of soil properties is a key prerequisite for the implementation of adaptive agrotechnologies aimed at increasing productivity and sustainability of agroecosystems. At the same time, such zones create different nutritional and growth conditions for plants, which can potentially affect grain quality formation. In the study by R. Łukowiak *et al*. (2024), it was demonstrated that spatial differences in soil mineral nitrogen content are closely related to crop productivity variability and nitrogen-use efficiency indicators. The authors emphasised that even within a single field there are zones with fundamentally different nitrogen supply conditions that respond differently to agrotechnical practices. Such differences may alter the balance between carbohydrate accumulation and nitrogen-containing compounds in grain, which is directly related to its quality indicators.

The physical condition of soil is also an important factor contributing to the spatial heterogeneity of agrocenoses. A. Romero-Ruiz *et al*. (2024) showed that spatially heterogeneous soil compaction significantly affects biomass growth, nutrient availability and root system functioning. These changes create local differences in the soil water-air regime and nutrient uptake, which may indirectly influence grain filling processes and its physico-chemical properties. Studies by E. Lippold *et al*. (2022) demonstrated that maize can partially compensate for soil heterogeneity through local adaptation of root system architecture. However, such adaptation does not always ensure uniform growth and productivity of plants in different field microzones. This means that under the same seeding rate, plants may form different individual productivity and potentially different grain quality depending on local soil conditions.

Physiological and molecular mechanisms of maize responses to changes in soil physico-chemical properties were described in detail by S. Zhou *et al*. (2024), who showed that uneven nitrogen distribution in soil causes significant differences in gene expression and root system development. The authors found that such differences result in asymmetric nutrient uptake and may affect the balance between vegetative growth and reproductive organ development. This creates prerequisites for variation in grain chemical composition across different field zones. In addition, S. Zhou *et al*. (2022) showed that the combination of variable nitrogen availability and intraspecific competition significantly affects maize root system development and plant biomass. As competition between plants increases, resource-use efficiency decreases, which is particularly evident at high seeding rates. This confirms the relevance of regulating plant density with consideration of field productivity zones to minimise competition and stabilise grain quality indicators.

The use of variable-rate seeding based on management zone maps is consistent with modern precision agriculture approaches. In particular, M.A. Munnaf *et al.* (2022) demonstrated that site-specific seeding, implemented based on multisensor field zoning, ensures more efficient spatial placement of plants and reduces intraspecific competition. The authors emphasised that combining productivity zones with variable seeding rates is a key factor in stabilising agronomic indicators within a field. The feasibility of optimising seeding rates with consideration of within-field heterogeneity is also supported by the findings of A.A. Anselmi *et al.* (2021), who showed that establishing maize plant density based on the potential productivity of management zones increases resource-use efficiency without yield loss. The authors noted that fixed seeding rates do not ensure realisation of the genetic potential of the crop under conditions of field spatial variability, whereas zone-adapted solutions create prerequisites for more stable formation of both yield and grain quality.

Thus, analysis of recent studies indicates that spatial heterogeneity of soil conditions and plant responses to within-field variability are key factors determining the effectiveness of agrotechnical decisions. At the same time, the influence of variable seeding rates on maize grain quality indicators under different field productivity zones remains insufficiently studied. This determines the relevance of research aimed at assessing the effects of field spatial heterogeneity and differentiated seeding rates on the physical and chemical quality indicators of maize grain.

The aim of the study was to determine the effects of field productivity zones and seeding rates on maize yield and grain quality indicators, as well as to identify optimal combinations of these factors for each zone in order to improve resource-use efficiency and yield quality stability under conditions of spatially heterogeneous agricultural landscapes.

Materials and Methods

The study was conducted during 2023-2025 on the fields of "Chernihiv Industrial Dairy Company" LLC, located in the Chernihiv district of Chernihiv region, within the transition zone between Polissia and the Forest-Steppe. The territory of the farm was characterised by a complex microrelief and high variability of soil cover, which created prerequisites for studying the response of maize to the spatial heterogeneity of agroecological conditions. The experiment was established according to a two-factor design. The first factor (A) was field productivity zones (high, medium and low), delineated on the basis of long-term maize yield maps, digital agrochemical map data and relief features, which corresponds to modern concepts of spatial heterogeneity of the soil-plant system and its influence on crop productivity (Havlin *et al.*, 2013).

Spatial variability of yield was determined using yield monitoring data from a grain harvester with a spatial resolution of 5 × 5 m, which were considered a reference source of information for analysing within-field variability of productivity and crop responses to growing conditions (Deines *et al.*, 2020). Productivity zones were formed using k-means cluster analysis in the QGIS environment, which enabled the grouping of field areas with similar yield characteristics and soil conditions into stable management zones recommended for differentiated agromanagement (Salem *et al.*, 2024). The identification of three productivity zones ensured an optimal balance between the level of detail of the field's spatial structure and the temporal stability of zones, which was critically important for further analysis of the effects of variable seeding rates on maize grain quality indicators.

The second factor (B) was maize seeding rate (65, 70, 75, 80 and 85 thousand seeds per hectare). Seeding rate treatments were implemented within each productivity zone using prescription maps for variable-rate seeding under different agroecological conditions of the field. The maize hybrid DKC 3939 of the medium-early maturity group was used in the experiment; it is characterised by high adaptability to changing hydrothermal growing conditions. The choice of this hybrid was justified by the results of field studies by O. Barabolia & I. Kosenko (2024), which demonstrated its stable yield under different sowing dates and variable temperature and moisture regimes, as well as higher productivity compared with other medium-maturity hybrids under optimal and later sowing dates.

Winter wheat was the preceding crop. The experiment was arranged in four replications across three experimental plots with an area of approximately 6.6 ha each. After crop emergence, actual plant density was checked to ensure compliance with the prescribed seeding rates. The fertilisation and crop protection system was uniform for all experimental treatments and corresponded to the farm's production technology, which minimised the influence of confounding factors on the formation of grain quality indicators. Weather conditions during the study years differed in terms of temperature regime and precipitation amount, which made it possible to assess the stability of the effects of seeding rates and productivity zones on grain quality indicators under different hydrothermal conditions. All fieldwork was carried out in compliance with national legislation of Ukraine, the principles of good scientific practice and international standards for the responsible use of plant resources, including the provisions of the Convention on Biological Diversity (1992).

Maize grain quality was assessed using the following indicators: grain test weight (g/L), thousand-kernel weight (g), protein content (%), starch content (%) and fat content (%). Grain test weight was determined using a standard one-litre measuring cylinder with control weighing in accordance with generally accepted methods specified in DSTU 10840:2019 (2019). Protein, starch and fat content in the grain were determined by infrared spectroscopy using an Infratec 1241 Grain Analyzer (FOSS Tecator, Denmark), previously calibrated in accordance with the requirements of ISO 12099:2017 (2017). Thousand-kernel weight was determined by weighing a sample of 1,000 kernels on analytical scales with an accuracy of ±0.01 g, in accordance with DSTU 4117:2007 (2007).

For each treatment, three composite grain samples were formed after post-harvest processing. The results were statistically analysed using analysis of variance and correlation analysis methods in the Statistica software. Mean values, standard deviations and coefficients of variation were calculated, and relationships between seeding rate, productivity zone and the main grain quality indicators were determined. Experimental data were visualised using modern graphical methods (boxplot, heat map), which made it possible to clearly illustrate the variability of grain quality indicators and the patterns of their change depending on seeding rate and productivity zone. Graphs were generated using the Python software environment.

Results

During the 2023-2025 research period, the formation of maize grain yield of the hybrid DKC 3939 was analysed depending on field productivity zones and variable seeding rates. The study covered three vegetation periods that were contrasting in terms of weather conditions, which made it possible to assess the stability of the crop response to agrotechnical factors under conditions of spatial heterogeneity of the agro-background. Despite year-to-year variability in yield caused by weather conditions, similar patterns of the effect of seeding rate within individual productivity zones were observed in all years. In the high-productivity zone, the highest mean grain yield over the three years of the study was obtained at a seeding rate of 80 thousand seeds per hectare, indicating the ability of this zone to effectively support increased plant density (Fig. 1).

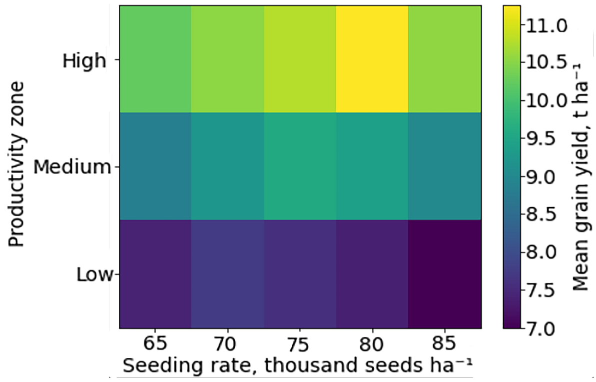

Figure 1. *Heat map of mean grain yield depending on productivity zone and seeding rate (2023-2025)*

Source: developed by the authors

At the same time, a further increase in the seeding rate to 85 thousand seeds per hectare did not provide an additional increase in yield, indicating that the optimal level of intraspecific competition had been reached. In the medium-productivity zone, the highest mean yield values were formed at a seeding rate of 75 thousand seeds per hectare, whereas an increase in plant density to 80-85 thousand seeds per hectare was accompanied by a decrease in the efficiency of resource use. In the low-productivity zone, a seeding rate of 70 thousand seeds per hectare proved to be optimal, while its further increase led to a reduction in yield, indicating the limited resource potential of this zone. The level of intraspecific competition, determined by the seeding rate and the resource potential of microzones, directly affects grain filling processes, which is reflected in test weight, thousand-kernel weight, as well as in the ratio of the main storage substances. In this regard, further analysis was focused on assessing the effect of productivity zones and variable seeding rates on starch, protein and fat content in maize grain (Table 1).

Table 1. *Test weight and thousand-kernel weight of maize depending on seeding rate and productivity zones (2023-2025)*

Productivity zone	Seeding rate, thousand seeds/ha	Test weight, g/L				Thousand-kernel weight, g			
		2023	2024	2025	Mean	2023	2024	2025	Mean
High	65	720	712	728	720	305	295	315	305
	70	722	714	730	722	308	298	318	308
	75	724	716	732	724	310	300	320	310
	80	726	718	736	727	312	302	325	313
	85	723	715	729	722	309	299	317	308
Mean value for the high-productivity zone		723	715	731	723	309	299	319	309
Medium	65	705	695	715	705	285	275	298	286
	70	708	698	718	708	288	278	302	289
	75	710	700	720	710	292	282	305	293
	80	709	699	719	709	290	280	303	291
	85	707	696	716	706	287	276	300	288
Mean value for the medium-productivity zone		708	698	718	708	288	278	302	289

Table 1. *Continued*

Productivity zone	Seeding rate, thousand seeds/ha	Test weight, g/L				Thousand-kernel weight, g			
		2023	2024	2025	Mean	2023	2024	2025	Mean
Low	65	690	670	695	685	270	245	275	263
	70	692	672	698	687	273	248	278	266
	75	691	671	697	686	271	247	277	265
	80	689	669	694	684	269	245	274	263
	85	685	665	690	680	265	240	270	258
Mean value for the low-productivity zone		689	669	695	685	270	245	275	263

Source: developed by the authors

Analysis of the data in Table 1 indicates that maize grain test weight and thousand-kernel weight varied significantly depending on the field productivity zone, seeding rate and growing season conditions. During 2023-2025, the highest values of both indicators were consistently formed in the high-productivity zone, reflecting more favourable grain filling conditions under a high soil resource potential.

In the high-productivity zone (Fig. 2), the multi-year average values of test weight increased with an increase in seeding rate from 65 to 80 thousand seeds per hectare (from 720 to 727 g/L).

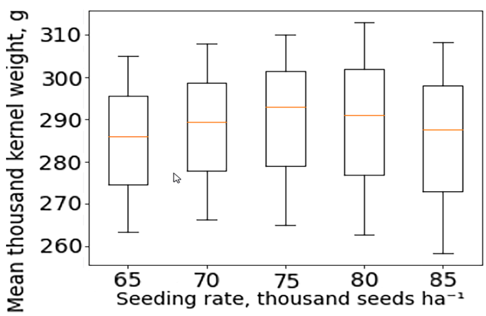

Figure 2. *Distribution of mean maize kernel weight according to seeding rates (2023-2025)*

Source: developed by the authors

With a further increase in the seeding rate to 85 thousand/ha, a slight decrease in the indicator was observed. A similar trend was observed for the weight of 1,000 grains, the maximum average value of which (313 g) was formed at a seeding rate of 80 thousand/ha (Fig. 3). This indicates an optimal combination of plant density and resource availability at this particular seeding rate.

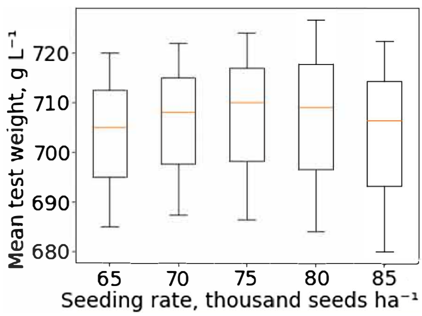

Figure 3. *Distribution of the mean weight of 1,000 maize kernels according to sowing rates (2023-2025)*

Source: developed by the authors

In the medium-productivity zone, test weight and thousand-kernel weight were lower than in the high-productivity zone; however, they retained a clear dependence on seeding rate. The highest mean values of test weight (710 g/L) and thousand-kernel weight (293 g) were observed at a seeding rate of 75 thousand seeds per hectare, whereas a further increase in plant density to 80-85 thousand seeds per hectare did not result in an improvement of grain physical properties (Figs 2 and 3). This indicates a limited resource potential of the medium-productivity zone and increased intraspecific competition at higher seeding rates.

In the low-productivity zone, the lowest values of both test weight and thousand-kernel weight were recorded, with a consistent downward trend as the seeding rate increased. The maximum mean values of test weight (687 g/L) and thousand-kernel weight (266 g) were formed at seeding rates of 65-70 thousand seeds per hectare, while an increase in density to 85 thousand seeds per hectare led to a significant deterioration of grain physical characteristics. This suggests that under conditions of low soil productivity, increased competition between plants restricts grain filling processes.

Analysis of the indicators by years showed that in 2025, higher values of test weight and thousand-kernel weight were formed across all productivity zones compared with 2023 and especially 2024, which was associated with more favourable growing conditions. At the same time, regardless of the year of cultivation, a general pattern was maintained: the optimal seeding rate shifted towards higher values in the high-productivity zone and decreased in the medium and low zones, confirming the feasibility of a differentiated approach to regulating plant density. Analysis of the data in Table 2 indicates that the chemical composition of maize grain depended significantly on the field productivity zone, seeding rate and growing season conditions. During 2023-2025, a clear differentiation between zones was observed, reflecting different levels of resource availability for crops and, consequently, the intensity of grain filling processes.

Table 2. *Protein, fat and starch content in maize grain depending on seeding rate and productivity zones (2023-2025)*

Productivity zone	Seeding rate, thousand seeds/ha	Protein content, %				Fat content, %				Starch content, %			
		2023	2024	2025	Mean	2023	2024	2025	Mean	2023	2024	2025	Mean
High	65	8.4	8.6	8.2	8.4	4.2	4.3	4.0	4.2	71.8	71.0	72.4	71.7
	70	8.3	8.5	8.1	8.3	4.1	4.2	3.9	4.1	72.0	71.2	72.7	72.0
	75	8.2	8.4	8.0	8.2	4.1	4.2	3.9	4.1	72.3	71.4	72.9	72.2
	80	8.1	8.3	7.8	8.1	4.0	4.1	3.8	4.0	72.6	71.6	73.4	72.5
	85	8.2	8.4	8.1	8.2	4.1	4.2	3.9	4.1	72.2	71.3	72.6	72.0
Mean value for the high-productivity zone, %		8.2	8.4	8.0	8.2	4.1	4.2	3.9	4.1	72.2	71.3	72.8	72.1
Medium	65	8.8	9.0	8.5	8.8	4.4	4.5	4.2	4.4	70.5	69.8	71.2	70.5
	70	8.7	8.9	8.4	8.7	4.3	4.4	4.1	4.3	70.8	70.0	71.5	70.8
	75	8.6	8.8	8.3	8.6	4.3	4.4	4.1	4.3	71.1	70.2	71.8	71.0
	80	8.6	8.8	8.4	8.6	4.3	4.4	4.1	4.3	70.9	70.1	71.6	70.9
	85	8.7	8.9	8.5	8.7	4.4	4.5	4.2	4.4	70.7	69.9	71.3	70.6
Mean value for the medium-productivity zone, %		8.7	8.9	8.4	8.7	4.3	4.4	4.1	4.3	70.8	70.0	71.5	70.8
Low	65	9.2	9.7	9.0	9.3	4.7	4.9	4.5	4.7	69.2	67.8	69.8	68.9
	70	9.1	9.6	8.8	9.2	4.6	4.8	4.4	4.6	69.5	68.0	70.2	69.2
	75	9.1	9.6	8.9	9.2	4.6	4.8	4.4	4.6	69.4	67.9	70.0	69.1
	80	9.3	9.8	9.1	9.4	4.7	4.9	4.6	4.7	69.1	67.7	69.7	68.8
	85	9.5	10	9.2	9.6	4.8	5.0	4.7	4.8	68.7	67.3	69.4	68.5
Mean value for the low-productivity zone, %		9.2	9.7	9.0	9.3	4.7	4,9	4.5	4.7	69.2	67.7	69.8	68.9

Source: developed by the authors

In the high-productivity zone, protein content was characterised by the lowest mean values (8.1-8.4%) compared with other zones, which was due to intensive starch accumulation and the manifestation of a "dilution" effect of nitrogen-containing compounds. At the same time, this zone exhibited the highest starch content, with mean values increasing as the seeding rate rose to 80 thousand seeds per hectare (72.5%), after which a tendency towards stabilisation or a slight decrease was observed. Fat content in the high-productivity zone remained relatively low (4.0-4.2%) and showed only a weak response to changes in seeding rate, which is typical of conditions of high productivity and the dominance of carbohydrate metabolism. In the medium-productivity zone, indicators of the chemical composition of grain had intermediate values. Protein content averaged 8.6-8.8% and varied only slightly depending on seeding rate, indicating a more balanced relationship between starch accumulation and nitrogen-containing compounds. The maximum mean starch content (71.0%) was formed at a seeding rate of 75 thousand seeds per hectare, whereas an increase in plant density to 80-85 thousand seeds per hectare did not result in its further increase. Fat content in the grain of the medium-productivity zone ranged from 4.3 to 4.4% and showed a weak response to changes in plant density. In the low-productivity zone, the highest values of protein and fat content were recorded simultaneously with the lowest starch content. Mean protein content increased from 9.3% at a seeding rate of 65 thousand seeds per hectare to 9.6% at 85 thousand seeds per hectare, which was associated with a reduction in the intensity of carbohydrate synthesis and a relative increase in nitrogen concentration in the grain. A similar trend was observed for fat content, which reached maximum values (4.8%) at the highest seeding rate. Starch content in the low-productivity zone decreased with increasing sowing density and had the lowest mean values (68.5-69.2%), indicating limitations in photosynthetic productivity and deterioration of grain filling conditions.

Analysis of the indicators by years showed that in 2025, higher starch content and lower protein and fat concentrations were formed across all productivity zones compared with 2024, which is consistent with more favourable growing conditions. At the same time, regardless of the year of cultivation, a general pattern was maintained: as the productive potential of the zone decreased, the proportion of protein and fat increased and starch content decreased, confirming a close relationship between yield and grain quality indicators.

Discussion

The results of the conducted studies convincingly demonstrate that spatial heterogeneity of the field is a key factor in the formation of both yield and the physical and chemical quality indicators of maize grain. During 2023-2025, it was established that the productivity zone determines the direction and intensity of the maize plant response to seeding rate, while plant density performs a regulatory function, the effectiveness of which varies depending on the resource potential of the agro-background. The feasibility of using spatial productivity categories for assessing crop condition and yield is also supported by recent studies by E. Birinyi *et al.* (2024), which demonstrated a close relationship between yield maps, satellite vegetation indices and actual yield losses at the field level.

The obtained results are consistent with data from a multiregional study conducted in China, which showed that the spatial distribution of grain quality indicators (starch, protein, fat and test weight) does not replicate yield maps and is formed under the combined influence of soil and climatic factors. In particular, W. Liu *et al.* (2023) identified a negative relationship between starch content and protein and fat concentrations, which is fully confirmed by the results of the present study for low-productivity field zones. Similar conclusions were reported by V. Babić *et al.* (2024), who showed that environmental conditions of the year and the growing environment have a decisive influence on the physical parameters of grain and its chemical composition, even at similar yield levels. The authors emphasised the protein “dilution” effect typical of intensive conditions, which was also observed in the present study in high-productivity zones under optimal seeding rates. Studies by D.J. Ogunniyan *et al.* (2021) demonstrated that thousand-kernel weight and seed morphometric characteristics are positively related to yield; however, under excessive plant density this relationship weakens due to limited resource availability for individual plants. A similar trend was recorded in the present study in medium- and low-productivity zones.

Under the conditions of Ukraine, the zonal specificity of optimal sowing density was confirmed in the work of M. Dudka & O.P. Yakunin (2023), which showed that increasing plant density is effective only up to a certain threshold, beyond which both yield and yield structure components decline. The results of the present study complement these findings by demonstrating that exceeding the optimal plant density also negatively affects grain quality. The inverse relationship between starch content and protein and fat concentrations identified in this study is consistent with the results of long-term research by D.S. Sachan *et al.* (2023), who showed that intensification of agrotechnologies and increased yield promote starch accumulation but reduce the relative protein content in grain. Although the authors primarily analysed the effect of nutrient supply, the mechanism of assimilate redistribution is universal and also relevant to the effects of plant density. Similar patterns were also reported by E.M.S. Gheith *et al.* (2022), who found that with increasing nitrogen nutrition levels and maize biomass, the relative protein concentration in grain decreases due to the dominance of carbohydrate metabolism. In the present study, this effect was clearly expressed in high-productivity zones under optimal seeding rates. The role of adaptive selection of seeding rate and nutrition under conditions of climatic variability was confirmed in the studies of S. Kothiyal *et al.* (2023) and G.K. Tadiboina *et al.* (2024), which showed that variable-rate seeding and fertilisation technologies based on productivity zones make it possible to stabilise maize productivity under diverse agroclimatic conditions. The results of the present study indicate that even under the contrasting weather conditions of 2023-2025, zonal patterns of grain quality formation remained stable. The results obtained are also consistent with data from on-farm experiments conducted by M. Videgain *et al.* (2024), in which differentiated management of seeding and fertilisation under semi-arid conditions allowed clear identification of zonal differences in crop response. The authors noted that the effect of precise regulation of agrotechnologies is manifested not only at the yield level but also through changes in the physical and quality characteristics of grain, which confirms the feasibility of a zone-oriented approach.

Thus, the results of the study are consistent with contemporary scientific concepts of spatially oriented maize crop management and extend them with new data on grain quality formation. It was established that optimisation of seeding rates should be zone-specific and aimed not only at maximising yield but also at the targeted formation of physical and chemical grain quality indicators. This confirms the feasibility of implementing variable-rate seeding (VRS) as an effective precision agriculture tool under conditions of spatially heterogeneous agroecosystems.

Conclusions

The studies conducted during 2023-2025 confirmed that the spatial heterogeneity of the field is a decisive factor in the formation of not only yield, but also the physical and chemical quality parameters of maize grain. The productivity zone had a significant effect on grain test weight, thousand-kernel weight, and the ratio of the main storage substances, while the seeding rate played a regulatory role, the effectiveness of which varied depending on the resource potential of a particular zone.

In the high-productivity zone, optimal nutrient supply and water availability contributed to the formation of grain with the highest test weight and thousand-kernel weight, as well as the maximum starch content combined with lower concentrations of protein and fat. Seeding rates of 75-80 thousand seeds per hectare were the most effective in this zone, ensuring an optimal balance between plant density and grain filling processes. A further increase in the seeding rate did not lead to an improvement in quality indicators, indicating that the limit of efficient resource use had been reached. In the medium-productivity zone, intermediate values of grain quality indicators were formed, and the optimum seeding rate shifted towards 70-75 thousand seeds per hectare. Increasing sowing density beyond this level was accompanied by a decrease in resource-use efficiency, which was reflected in the stabilisation or slight deterioration of test weight, thousand-kernel weight and starch content. This indicates the limited resource potential of medium-productivity zones and the need for a more cautious approach to increasing sowing density. In the low-productivity zone, the lowest values of test weight and thousand-kernel weight were recorded, together with the highest concentrations of protein and fat and a reduced starch content. Lower seeding rates (65-70 thousand seeds per hectare) were optimal for this zone, whereas increasing them intensified intraspecific competition, limited grain filling processes and led to a deterioration of grain physical characteristics. These patterns indicate the limiting influence of soil and hydrological conditions in low-productivity areas.

Despite interannual variability in weather conditions, the established patterns of the effects of productivity zones and seeding rates on grain quality indicators were maintained in all years of the study. This confirms the dominant role of spatial differences in the soil resource potential of the field over seasonal climatic variability in the formation of maize grain quality. The prospects for further research lie in the scientific substantiation of the feasibility of applying precision agriculture technologies, in particular variable-rate seeding (VRS), taking into account field productivity zones, as differentiated regulation of plant density allows not only the stabilisation of yield but also targeted influence on maize grain quality parameters, increasing seed-use efficiency and the adaptability of the technology to the spatial heterogeneity of agroecosystems.

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Conflict of Interest

None.

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Формування показників якості зерна кукурудзи за впливу норм висіву та зон продуктивності поля

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Анотація. Якість зерна кукурудзи є важливим показником ефективності агротехнологій і формується під впливом просторової неоднорідності ґрунтово-кліматичних умов та рівня внутрішньоценозної конкуренції. Метою дослідження було встановити вплив зон продуктивності поля та змінних норм висіву на урожайність і показники якості зерна кукурудзи, зокрема натуру, масу 1000 зерен, вміст крохмалю, білка та жиру. Польові дослідження проводили упродовж 2023-2025 рр. у межах трьох зон продуктивності поля (високої, середньої та низької), виділених на основі багаторічних карт урожайності та просторового аналізу. Дослід закладали з використанням п'яти норм висіву – 65, 70, 75, 80 та 85 тис. насінин/га. Результати досліджень показали, що зона продуктивності була домінуючим чинником формування урожайності та якісних показників зерна, тоді як норма висіву визначала ступінь реалізації потенціалу в межах кожної зони. Найвища середня урожайність (11,3 т/га) сформувалася у високопродуктивній зоні за норми висіву 80 тис. насінин/га, тоді як у низькопродуктивній зоні максимальні показники не перевищували 7,7 т/га. Натура зерна та маса 1000 зерен знижувалися у напрямку від високих до низьких зон продуктивності, що свідчить про погіршення умов наливу зерна за обмеженого ресурсного забезпечення. Вміст крохмалю був вищим у високопродуктивних зонах (у середньому до 72,5 %), тоді як у середніх і низьких зонах спостерігалося підвищення концентрації білка та жиру, що відображає адаптивну реакцію культури на стресові умови та зниження врожайності. Отримані результати підтверджують доцільність застосування зонально диференційованих норм висіву як інструменту одночасної оптимізації урожайності та якості зерна кукурудзи

Ключові слова: *Zea mays* L.; урожайність; показники якості зерна; натура; маса 1000 зерен; вміст крохмалю; білка і жиру; диференційована сівба; зона продуктивності