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Influence of growth regulators on winter wheat varieties yield and grain quality

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Abstract. Plant growth regulators are important tools for improving the productivity and technological quality of cereal crops under unstable environmental conditions. In winter wheat, triazole-derived compounds may enhance photosynthetic activity, optimize assimilate redistribution, improve grain filling, and contribute to higher and more stable grain yield. In the present study, seeds of five winter wheat varieties (Khvylia Dnipra, MIP Roksolana, Vezha, LG Magirus, and LG Litopys) were treated before sowing with aqueous solutions of two new triazole-type compounds, CA-64 (potassium [1,2,4]triazolo[1,5-c]quinazoline-2-thiolate) and CA-79 (potassium tetrazolo[1,5-c]quinazoline-5-thiolate), at concentrations of 0.01%, 0.02%, and 0.04%. Seeds were soaked for 24 h, and water-treated seeds served as the control. Field experiments were conducted during 2023–2025 under steppe conditions of the Prydniprovia. The compounds were evaluated for their effects on photosynthetic activity (SPAD and chlorophyll content), grain yield, yield-structure traits, and grain quality parameters, including protein, gluten, glutenin fractions, and gliadins. The results showed a clear concentration-dependent response. The concentrations 0.01% and especially 0.02% stimulated most of the studied traits, whereas 0.04% caused a depressive effect. The transition between stimulation and inhibition occurred within a relatively narrow concentration range, underscoring the critical importance of precise dose selection. Among the two tested compounds, CA-79 should be considered the more promising option, as it produced stronger improvements in photosynthetic activity, grain yield, yield structure, and most grain-quality traits. In nearly all varieties, CA-79 proved to be more effective than CA-64, particularly at 0.02%, producing the highest increases in photosynthetic activity, grain yield, grain weight per main spike, grain weight per plant, and thousand-grain weight. Positive effects on grain quality were also recorded, especially for protein, gluten and HMW glutenins, although quality traits responded less strongly than productivity traits. The strongest positive responses were observed in the varieties LG Magirus, LG Litopys, and MIP Roksolana, while Vezha also reacted positively but somewhat more moderately. The concentration 0.04% was excessive for both compounds and led to reduced physiological and agronomic performance. Thus, CA-79 at 0.02% can be recommended as the most effective option for improving photosynthetic activity, productivity, yield structure, and technological grain quality in winter wheat, whereas CA-64 at 0.02% may be considered a practical alternative. Further research should integrate field-based evaluation with more focused physiological and molecular studies, particularly those addressing biochemical regulation, antioxidant metabolism, assimilate distribution, and the synthesis of storage proteins.

Keywords: cereals; genotype; triazols; grain production; wheat; protein quality; photosintetic activity.

Introduction

Winter wheat is one of the leading crops that underpins food security, since cereals constitute the basis of both human nutrition and the feed base of livestock production. In terms of sown area and gross output, *Triticum aestivum* L. consistently ranks as one of the leading crop. At the same time, under production conditions, the potential of yield and grain quality is not fully realized because of a complex of unfavorable factors, including environmental stresses, nutrient deficiencies, drought, lodging, disease damage, and other limitations. In this regard, the role of plant growth regulators (synthetic and natural compounds capable of influencing growth, development, and yield formation) has increased substantially (Nazarenko et al., 2023; Jiacheng et al., 2026).

Growth regulators are biologically active substances that exert their effect even at very low concentrations by modifying the course of physiological and biochemical processes in plants. They may either mimic or suppress the action of natural phytohormones, including auxins, cytokinins, gibberellins, abscisic acid, and ethylene. For cereal crops, the greatest interest is in triazole regulators such as paclobutrazol, uniconazole, tebuconazole, and triadimenol, which reduce stem height, limit lodging, increase lignin content, and improve water relations. Alongside them, important roles are played by preparations based on humic and fulvic acids, which stimulate root system development and improve nutrient availability, as well as amino acid and peptide complexes that alleviate the effects of abiotic stress and support photosynthetic activity, and epigenetically active compounds involved in the formation of adaptive responses at the gene-expression level. Owing to these properties, growth regulators are regarded as an important element of ecologically sound crop intensification (Khalil et al., 2021; Wang et al., 2025).

Wheat is characterized by high sensitivity to growing conditions. Its productivity to a large extent depends on resistance to lodging, drought, and diseases, as well as on the complete formation of yield components such as the number of productive stems, spike length, grain number, and grain filling. The use of growth regulators makes it possible to influence these traits in a targeted way. In particular, triazole preparations contribute to improved lodging resistance through internode shortening and strengthening of cell walls via increased lignin and cellulose content. This reduces the risk of yield losses caused by strong winds and heavy rainfall. In addition, regulators are capable of enhancing photosynthetic activity by increasing leaf area, chlorophyll concentration, and the duration of active functioning of the photosynthetic apparatus. As a result, plants use light energy more efficiently and accumulate more carbohydrates, which are subsequently directed toward grain filling (Peng et al., 2025).

The use of growth-regulating preparations and amino acid complexes promotes the formation of a deeper and more branched root system, thereby improving the uptake of water and mineral nutrients. Under conditions of high temperature, drought, or salinity, growth regulators activate antioxidant enzymes, particularly superoxide dismutase and catalase, stabilize cell membranes, and stimulate the accumulation of osmotically active compounds such as proline and sugars. It has also been established that

certain regulators are able to increase protein and gluten content in grain, which is of particular importance for the baking value of wheat (Rozman et al., 2025; Zhao et al., 2025).

Results of studies conducted in Ukraine and abroad confirm that the application of triazole regulators can enhance wheat yield by up to 10–15%, depending on the variety and the conditions of a given year. For example, experiments with paclobutrazol have recorded a 70–80% reduction in lodging together with an increase in grain number per spike. The use of uniconazole in combination with micronutrients provided a 0.5–1.0% increase in grain protein content (Obaid et al., 2025; Singh et al., 2026a).

The use of growth-regulating substances in the steppe zone of Ukraine has also contributed to improved drought tolerance, which in turn ensured increased yields even under precipitation deficit. Similar results have been obtained in barley and maize. It is also important that growth regulators have a number of additional advantages: They improve the efficiency of nitrogen and water use, meaning that fertilizer rates and irrigation can be reduced. In years with unfavorable weather conditions, such preparations help avoid substantial yield losses. Most modern growth regulators are applied at very low concentrations, within the range of 0.01–0.10%, which does not cause hazardous accumulation in soil or products (Alebidi et al., 2026; Jiacheng et al., 2026).

Despite their obvious advantages, the widespread introduction of growth regulators into agricultural practice is limited by several factors. These include insufficient awareness among producers regarding optimal methods and timing of application, the need for variety-specific studies due to the unequal response of different wheat genotypes to the same preparations, and the insufficient level of governmental support for the implementation of modern technologies in small and medium-sized farms. At the same time, the development of agronomy indicates a continued growing importance of growth regulators. The creation of combined preparations that unite growth regulators with micronutrients, biostimulants, and microbial inoculants is considered especially promising (Garrido-Auñón et al., 2025).

Thus, the use of growth regulators is an important component of crop intensification aimed at increasing yield and improving the quality of grain products, primarily in cereal crops. Their action is complex in nature and includes enhancement of resistance to stress factors, prevention of lodging, improvement of photosynthesis, root nutrition, and baking properties of grain. Under conditions of climate change, deficits of water and mineral resources, and growing demand for high-quality food products, growth regulators are becoming one of the key tools of sustainable agricultural production (Wang et al., 2022).

The objective of our study was to evaluate the practical potential of two new compounds, CA-64 (potassium [1,2,4]triazolo[1,5-c]quinazoline-2-thiolate) and CA-79 (potassium tetrazolo[1,5-c]quinazoline-5-thiolate), as plant growth regulators, by determining their ability to increase the photosynthetic activity, yield, and grain quality of winter wheat, and to clarify the specific features of their effect on yield structure components in order to substantiate changes in grain productivity.

Materials and methods

Field experiments were conducted over the 2023–2025 growing seasons at the experimental station of the Department of Breeding and Seedfarming, Dnipro State Agrarian and Economic University, located in the steppe zone under subhumid conditions. The study focused on the presowing treatment of bread wheat seeds with aqueous solutions of two triazole-derived compounds: CA-64 (potassium [1,2,4]triazolo[1,5-c]quinazoline-2-thiolate) and CA-79 (potassium tetrazolo[1,5-c]quinazoline-5-thiolate). For each treatment and the corresponding water control, 1,000 seeds were soaked for 24 h. Both compounds were tested at 0.01%, 0.02%, and 0.04% concentrations, and the selected concentration range was based on previous studies of chemically related compounds in cereal crops (Nazarenko & Khoroshun, 2025). The combination of the varietal panel with the seed-treatment schemes, including the untreated control, generated 40 variety × treatment combinations.

The plant material included both locally bred winter wheat varieties, such as MIP Roksolana, Vezha, and Khvylia Dnipra, and western-ecotype genotypes, including Magirus and LG Litopys. Each experimental unit occupied a 10 m² plot, arranged with 0.15 m row spacing and 6.5 m row length. The trial was established in a regular layout with three replications, whereas the standard control was included once within each experiment. Seeding rates were adjusted according to the thousand-grain weight (TGW) of the respective variety. Crop cultivation and plant protection practices followed regional recommendations for the subhumid steppe zone in order to minimize interference from uncontrolled pest and disease development.

Observations covered the entire growing period. Phenological stages were recorded systematically, and during heading, the degree of leaf greenness was measured using a SPAD-502 chlorophyll meter. Total chlorophyll concentration (a + b) was then estimated from SPAD readings according to the commonly applied relationship $Chl = 10M^{0.265}$, where M represents SPAD units (Vesali et al., 2017). To characterize yield formation, a structural analysis was carried out on 25–30 well-developed plants selected from each treatment. These plants were measured and threshed individually to determine plant height, grain number and grain weight from the main spike, grain weight per plant, the share of grain in total plant productivity, and TGW. Grain quality was assessed by measuring protein content with a Spektran-119R analyzer designed for protein and gluten determination, using a 10 g sample.

To evaluate relationships among traits and identify the most informative indicators of treatment response, linear discriminant analysis (LDA) was applied. This multivariate approach allowed estimation of trait loadings and made it possible to identify variables with the greatest discriminating power among the tested compound × concentration classes. It also provided cross-validated classification accuracy, which is valuable for practical decision-making regarding the seed-priming regimes most likely to produce desired phenotypic shifts.

All statistical analyses were performed in Statistica 10.0 (TIBCO, Palo Alto, USA). The data were processed using factorial analysis of variance (ANOVA) with genotype (variety), compound identity, and concentration treated as fixed factors, together with their interactions. The assumption of normality was checked using the Shapiro–Wilk W-test. When necessary, the data were transformed or analyzed with methods appropriate to the observed distribution. For all measured traits, descriptive statistics were calculated as means ± standard deviations, and graphical presentation was used to facilitate the interpretation of treatment effects. Whenever ANOVA indicated significance at $P < 0.05$, differences among group means were separated using Tukey's HSD test.

Results

The data presented in Table 1 show that the photosynthetic activity of winter wheat was clearly dependent on both the compound applied and its concentration, and these changes were well reflected by both indicators, SPAD and chlorophyll content (Chl). CA-79 was generally more effective than CA-64 across almost all varieties and concentrations. On average across all varieties, the baseline level was about 50.45 SPAD and 674.15 µmol/cm² of chlorophyll. Under the action of CA-64 0.01%, these values increased to 54.81 SPAD and 783.77 µmol/cm², that is, by 4.36 SPAD units (+8.7%) and 109.62 µmol/cm² (+16.3%), respectively. At 0.02% concentration, CA-64 produced the highest effect, reaching 59.35 SPAD and 905.12 µmol/cm², or +17.6% and +34.3% relative to the control. By contrast, CA-64 0.04% reduced the indicators to 46.24 SPAD and 584.90 µmol/cm², that is, 8.3% and 13.2% below the control, respectively.

For CA-79, the effect was even more pronounced. At 0.01%, the mean values increased to 55.82 SPAD and 810.74 µmol/cm², which corresponds to +10.6% and +20.3% relative to the control. The strongest stimulation was observed at CA-79 0.02%, with the average values reaching 60.86 SPAD and 945.57 µmol/cm², that is, +20.6% for SPAD and +40.3% for chlorophyll. At 0.04% CA-79, suppression was already observed, with the values decreasing to 47.24 SPAD and 605.12 µmol/cm², which is 6.4% and 10.2% below the control, respectively. Thus, the best treatment overall was CA-79 0.02%, followed by CA-64 0.02%.

The highest initial photosynthetic potential in the control was observed in LG Magirus and LG Litopys. Their standard values were 54.57 and 54.56 SPAD, respectively, while chlorophyll content reached 772.86 and 768.79 µmol/cm². These values were markedly higher than those recorded for Khvylia Dnipra, MIP Roksolana, and Vezha, whose control values ranged from 47.41 to 47.88 SPAD and from 606.00 to 611.58 µmol/cm². Therefore, LG Magirus and LG Litopys should be regarded as the varieties with the highest initial photosynthetic potential.

At the same time, all varieties responded well to the stimulatory concentrations. Under CA-64 0.02%, the chlorophyll content in Khvylia Dnipra increased from 47.82 to 56.19 SPAD and from 611.58 to 819.52 µmol/cm², while under CA-79 0.02% the corresponding values

rose to 57.62 SPAD and 856.21 μmol/cm². MIP Roksolana also showed a strong response: Under CA-79 0.02%, the parameters increased from 47.41 to 56.65 SPAD and from 606.00 to 839.92 μmol/cm². Vezha showed a similar reaction under CA-79 0.02% – 57.46 SPAD and 851.83 μmol/cm², compared with 47.88 SPAD and 611.51 μmol/cm² in the control. The highest absolute values were recorded for LG Magirus and LG Litopys specifically under CA-79 0.02%, namely 66.19–66.40 SPAD and 1089.22–1090.66 μmol/cm². This means that the foreign varieties not only had a higher natural potential, but also realized it most effectively under optimal stimulation.

Table 1

Parameters of photosynthetic activity CA-action (x ± SD, n = 5)

Variant	Soil plant analysis development (SPAD)	Chl, μmol/cm²	Variant	Soil plant analysis development (SPAD)	Chl, μmol/cm²
Khvylia Dnipra	47.82 ± 1.39[a]	611.58 ± 11.62	Khvylia Dnipra	47.82 ± 1.39[a]	611.58 ± 11.62
Khvylia Dnipra, CA-64 0.01%	51.88 ± 1.32[b]	709.43 ± 11.91	Khvylia Dnipra, CA-79 0.01%	52.84 ± 1.35[b]	733.90 ± 11.41
Khvylia Dnipra, CA-64 0.02%	56.19 ± 1.42[c]	819.52 ± 11.17	Khvylia Dnipra, CA-79 0.02%	57.62 ± 1.44[c]	856.21 ± 11.91
Khvylia Dnipra, CA-64 0.04%	43.76 ± 1.32[d]	529.02 ± 11.17	Khvylia Dnipra, CA-79 0.04%	44.71 ± 1.32[d]	547.36 ± 11.91
MIP Roksolana	47.41 ± 1.17[a]	606.00 ± 11.21	MIP Roksolana	47.41 ± 1.17[a]	606.00 ± 11.21
MIP Roksolana, CA-64 0.01%	50.97 ± 1.13[b]	694.48 ± 11.50	MIP Roksolana, CA-79 0.01%	51.91 ± 1.15[b]	718.72 ± 10.76
MIP Roksolana, CA-64 0.02%	55.23 ± 1.20[c]	803.56 ± 11.00	MIP Roksolana, CA-79 0.02%	56.65 ± 1.13[c]	839.92 ± 11.39
MIP Roksolana, CA-64 0.04%	42.91 ± 1.20[d]	515.71 ± 11.50	MIP Roksolana, CA-79 0.04%	43.85 ± 1.15[d]	533.89 ± 11.07
Vezha	47.88 ± 1.28[a]	611.51 ± 11.61	Vezha	47.88 ± 1.28[a]	611.51 ± 11.61
Vezha, CA-64 0.01%	51.71 ± 1.24[b]	705.07 ± 11.40	Vezha, CA-79 0.01%	52.67 ± 1.21[b]	729.53 ± 11.47
Vezha, CA-64 0.02%	56.02 ± 1.26[c]	815.14 ± 11.16	Vezha, CA-79 0.02%	57.46 ± 1.26[c]	851.83 ± 11.90
Vezha, CA-64 0.04%	43.57 ± 1.21[d]	524.68 ± 11.79	Vezha, CA-79 0.04%	44.53 ± 1.26[d]	543.02 ± 11.16
LG Magirus	54.57 ± 0.90[a]	772.86 ± 9.21	LG Magirus	54.57 ± 0.90[a]	772.86 ± 9.21
LG Magirus, CA-64 0.01%	59.65 ± 0.93[b]	905.17 ± 9.50	LG Magirus, CA-79 0.01%	60.74 ± 0.88[b]	936.09 ± 9.50
LG Magirus, CA-64 0.02%	64.56 ± 0.86[c]	1044.29 ± 9.39	LG Magirus, CA-79 0.02%	66.19 ± 0.88[c]	1090.66 ± 9.50
LG Magirus, CA-64 0.04%	50.37 ± 0.86[d]	677.18 ± 9.50	LG Magirus, CA-79 0.04%	51.46 ± 0.86[d]	700.37 ± 8.76
LG Litopys	54.56 ± 1.03[a]	768.79 ± 10.24	LG Litopys	54.56 ± 1.03[a]	768.79 ± 10.24
LG Litopys, CA-64 0.01%	59.85 ± 0.96[b]	904.71 ± 10.03	LG Litopys, CA-79 0.01%	60.94 ± 1.06[b]	935.46 ± 10.10
LG Litopys, CA-64 0.02%	64.76 ± 1.01[c]	1043.09 ± 9.79	LG Litopys, CA-79 0.02%	66.40 ± 1.06[c]	1089.22 ± 10.10
LG Litopys, CA-64 0.04%	50.58 ± 0.99[d]	677.92 ± 9.79	LG Litopys, CA-79 0.04%	51.67 ± 0.99[d]	700.98 ± 10.10

Note: significant differences at $P < 0.05$ were estimated within each variety across treatment concentrations.

Photosynthetic activity in winter wheat was enhanced most strongly at 0.02%, with CA-79 being more effective than CA-64. The concentration 0.01% also acted positively, though less strongly, whereas 0.04% for both compounds already had a suppressive effect. In terms of initial photosynthetic potential, LG Magirus and LG Litopys were the leading varieties, while Khvylia Dnipra, MIP Roksolana, and Vezha had a lower baseline level of the trait but nevertheless showed a clearly positive response to the optimal concentrations. Therefore, for improving photosynthetic activity, the most promising treatment is CA-79 at 0.02%, while CA-64 at 0.02% may be considered an alternative.

For both tested compounds, the response pattern was consistent: 0.01% and 0.02% stimulated photosynthetic activity, whereas 0.04% produced a depressive effect. At the same time, the expression of this trait varied markedly among genotypes, indicating that the effectiveness of CA treatment depended not only on dose but also on varietal background. Statistical analysis confirmed that photosynthetic performance was significantly influenced both by the genetic characteristics of the variety ($F = 8.34$; $F_{0.05} = 2.45$; $P = 0.009$) and by the concentration of the CA compound ($F = 27.82$; $F_{0.05} = 2.11$; $P = 1.16 \times 10^{-5}$). This parameter is especially informative because it reflects the action of the treatments at a critical ontogenetic stage directly related to grain yield formation. Moreover, the analysis revealed a statistically significant genotype × CA-agent interaction ($F = 7.35$; $F_{0.05} = 4.74$; $P = 0.01$), demonstrating that both the strength and the direction of the response were determined by the particular variety × compound combination rather than by the treatment alone.

For CA-64 (Table 2), a clear concentration-dependent response was observed. On average across all varieties, the control yield was 8.08 t/ha; at 0.01% it increased to 8.48 t/ha (+0.39 t/ha), at 0.02% to 8.77 t/ha (+0.69 t/ha), whereas 0.04% reduced it to 7.74 t/ha (–0.34 t/ha relative to the control). Thus, for CA-64, 0.02% was the most effective concentration, 0.01% also acted positively, while 0.04% had a suppressive effect.

In the control, Khvylia Dnipra produced an average yield of 8.23 t/ha. At 0.01%, the yield increased to 8.59 t/ha, and at 0.02% to 8.89 t/ha, corresponding to a gain of 0.66 t/ha. At 0.04%, the value declined to 7.85 t/ha, which was below the control level. This indicates a good response of the variety to moderate doses of the compound and a negative response to the high dose. MIP Roksolana had a control mean yield of 8.18 t/ha. The 0.01% treatment increased it to 8.60 t/ha and 0.02% to 8.90 t/ha (0.72 t/ha). At 0.04%, the yield declined to 7.85 t/ha. Thus, this variety responded well to the stimulatory concentrations, especially to 0.02%. Vezha had the lowest control value, 7.78 t/ha, but also responded well to treatment: 8.10 t/ha at 0.01% and 8.38 t/ha at 0.02% (0.60 t/ha). The high concentration 0.04% reduced yield to 7.39 t/ha, that is, below the control. Among the foreign varieties, LG Magirus produced 8.21 t/ha in the control, 8.65 t/ha at 0.01%, and 8.96 t/ha at 0.02%. This was the highest mean value for CA-64 and one of the best overall. The increase relative to the control was 0.75 t/ha, indicating that this variety realized the positive effect of CA-64 very well. At 0.04%, the yield declined to 7.91 t/ha. LG Litopys also responded well to the compound, from 8.02 t/ha in the control to 8.45 t/ha at 0.01% and 8.74 t/ha at 0.02% (0.72 t/ha). The 0.04% treatment reduced the value to 7.72 t/ha. Thus, under CA-64, all varieties showed the same general response pattern: 0.02% > 0.01% > control > 0.04%.

For CA-79 (Table 3), the concentration pattern was the same, but the stimulatory effect was more pronounced than for CA-64. On average across all varieties, the control yield was again 8.08 t/ha, but at 0.01% it increased to 8.67 t/ha (+0.59 t/ha), and at 0.02% to 8.99 t/ha (+0.91 t/ha). The high concentration 0.04% reduced the mean value to 7.80 t/ha (–0.29 t/ha). Thus, CA-79 was generally more effective than CA-64, and its optimal concentration was also 0.02%.

Under the influence of CA-79 0.01%, Khvylia Dnipra increased its mean yield from 8.23 to 8.80 t/ha and at 0.02% to 9.13 t/ha. This represents a very high increase of 0.90 t/ha. At 0.04%, the yield decreased to 7.90 t/ha. MIP Roksolana showed one of the best responses in the entire experiment: from 8.18 t/hain the control to 8.81 t/ha at 0.01%, and 9.13 t/ha at 0.02%, that is, an increase of 0.95 t/ha. At 0.04%, the yield dropped to 7.91 t/ha. Vezha also responded clearly positively: 7.78 t/hain the control, 8.30 t/ha at 0.01%, and 8.60 t/ha at 0.02% (0.82 t/ha). The high concentration reduced the yield to 7.44 t/ha.

Among the foreign varieties, LG Magirus was one of the most productive: 8.21 t/ha in the control, 8.81 t/ha at 0.01%, and 9.12 t/ha at 0.02% (+0.91 t/ha). At 0.04%, the value declined to 7.97 t/ha. LG Litopys also responded very well to CA-79, with the yield increasing from 8.02 t/ha in the control to 8.65 t/ha at 0.01% and 8.97 t/ha at 0.02% (+0.95 t/ha). At 0.04%, the yield decreased to 7.77 t/ha.

Thus, for CA-79 as well, all varieties showed the same order of concentration effectiveness: 0.02% > 0.01% > control > 0.04%, but the absolute yield increases were greater than under CA-64.

Both compounds were able to stimulate yield formation only at low and medium concentrations, whereas 0.04% was undesirable for both because of its clearly expressed depressive effect. At the same time, there was a substantial difference between the compounds: CA-64 at 0.02% promoted an average yield of 8.77 t/ha, while CA-79 at 0.02% promoted 8.99 t/ha. Thus, the advantage of CA-79 0.02% over CA-64 0.02% was about +0.22 t/ha on average across varieties. At 0.01%, the difference was also in favor of CA-79: 8.67 t/ha versus 8.48 t/ha, that is, approximately

+0.20 t/ha. Therefore, CA-79 should be regarded as the stronger yield stimulant, whereas CA-64 was also effective, although somewhat weaker.

In terms of the maximum realized yield potential under treatment, the leading varieties were Khvylia Dnipra with 9.13 t/ha (CA-79 0.02%), MIP Roksolana with 9.13 t/ha (CA-79 0.02%) and LG Magirus with 9.12 t/ha (CA-79 0.02%). Slightly lower values were observed in LG Litopys with 8.97 t/ha (CA-79 0.02%) and Vezha with 8.60 t/ha (CA-79 0.02%). With respect to responsiveness to stimulation, the largest increases were recorded in MIP Roksolana and LG Litopys under CA-79 0.02%, each showing an increase of 0.95 t/ha, followed by LG Magirus with 0.91 t/ha, Khvylia Dnipra with 0.90 t/ha, and Vezha with 0.82 t/ha. Thus, Vezha had the lowest initial level and the smallest absolute gain, although its response remained clearly positive. LG Magirus combined a high control background with a strong response to treatment, making it one of the most promising varieties. LG Litopys started from a lower level but realized the stimulatory effect well, especially under CA-79.

Table 2

Yield under action of CA-64 (x ± SD, n = 9)

Variant	Yield, t/ha			
	2023	2024	2025	Average
Khvylia Dnipra	8.16 ± 0.12^{a}	8.57 ± 0.13^{a}	7.95 ± 0.11^{a}	8.23 ± 0.13^{a}
Khvylia Dnipra, CA-64 0.01%	8.53 ± 0.11^{b}	8.93 ± 0.12^{b}	8.32 ± 0.11^{b}	8.59 ± 0.11^{b}
Khvylia Dnipra, CA-64 0.02%	8.85 ± 0.10^{c}	9.24 ± 0.11^{c}	8.59 ± 0.10^{c}	8.89 ± 0.10^{c}
Khvylia Dnipra, CA-64 0.04%	7.83 ± 0.10^{d}	8.17 ± 0.11^{d}	7.54 ± 0.10^{d}	7.85 ± 0.10^{d}
MIP Roksolana	8.06 ± 0.12^{a}	8.33 ± 0.13^{a}	8.16 ± 0.11^{a}	8.18 ± 0.13^{a}
MIP Roksolana, CA-64 0.01%	8.47 ± 0.11^{b}	8.73 ± 0.12^{b}	8.59 ± 0.11^{b}	8.60 ± 0.11^{b}
MIP Roksolana, CA-64 0.02%	8.79 ± 0.10^{c}	9.03 ± 0.11^{c}	8.87 ± 0.10^{c}	8.90 ± 0.10^{c}
MIP Roksolana, CA-64 0.04%	7.78 ± 0.10^{d}	7.99 ± 0.11^{d}	7.79 ± 0.10^{d}	7.85 ± 0.10^{d}
Vezha	7.70 ± 0.12^{a}	8.14 ± 0.13^{a}	7.51 ± 0.11^{a}	7.78 ± 0.13^{a}
Vezha, CA-64 0.01%	8.02 ± 0.11^{b}	8.45 ± 0.12^{b}	7.83 ± 0.11^{b}	8.10 ± 0.11^{b}
Vezha, CA-64 0.02%	8.32 ± 0.10^{c}	8.74 ± 0.11^{c}	8.09 ± 0.10^{c}	8.38 ± 0.10^{c}
Vezha, CA-64 0.04%	7.35 ± 0.10^{d}	7.72 ± 0.11^{d}	7.10 ± 0.10^{d}	7.39 ± 0.10^{d}
LG Magirus	7.99 ± 0.12^{a}	8.52 ± 0.13^{a}	8.11 ± 0.11^{a}	8.21 ± 0.13^{a}
LG Magirus, CA-64 0.01%	8.43 ± 0.11^{b}	8.96 ± 0.12^{b}	8.57 ± 0.11^{b}	8.65 ± 0.11^{b}
LG Magirus, CA-64 0.02%	8.75 ± 0.10^{c}	9.27 ± 0.11^{c}	8.85 ± 0.10^{c}	8.96 ± 0.10^{c}
LG Magirus, CA-64 0.04%	7.74 ± 0.10^{d}	8.20 ± 0.11^{d}	7.78 ± 0.10^{d}	7.91 ± 0.10^{d}
LG Litopys	7.84 ± 0.12^{a}	8.58 ± 0.13^{a}	7.65 ± 0.11^{a}	8.02 ± 0.13^{a}
LG Litopys, CA-64 0.01%	8.26 ± 0.11^{b}	9.01 ± 0.12^{b}	8.07 ± 0.11^{b}	8.45 ± 0.11^{b}
LG Litopys, CA-64 0.02%	8.57 ± 0.10^{c}	9.32 ± 0.11^{c}	8.33 ± 0.10^{c}	8.74 ± 0.10^{c}
LG Litopys, CA-64 0.04%	7.58 ± 0.10^{d}	8.25 ± 0.11^{d}	7.32 ± 0.10^{d}	7.72 ± 0.10^{d}

Note: values within each variety followed by different letters differ significantly ($P < 0.05$) for CA-64 treatment concentrations.

Table 3

Yield under action of CA-79 (x ± SD, n = 9)

Variant	Yield, t/ha			
	2023	2024	2025	Average
Khvylia Dnipra	8.16 ± 0.12^{a}	8.57 ± 0.13^{a}	7.95 ± 0.11^{a}	8.23 ± 0.13^{a}
Khvylia Dnipra, CA-79 0.01%	8.74 ± 0.11^{b}	9.14 ± 0.12^{b}	8.52 ± 0.11^{b}	8.80 ± 0.11^{b}
Khvylia Dnipra, CA-79 0.02%	9.07 ± 0.10^{c}	9.49 ± 0.11^{c}	8.82 ± 0.10^{c}	9.13 ± 0.10^{c}
Khvylia Dnipra, CA-79 0.04%	7.90 ± 0.10^{d}	8.22 ± 0.11^{d}	7.59 ± 0.10^{d}	7.90 ± 0.10^{d}
MIP Roksolana	8.06 ± 0.12^{a}	8.33 ± 0.13^{a}	8.16 ± 0.11^{a}	8.18 ± 0.13^{a}
MIP Roksolana, CA-79 0.01%	8.68 ± 0.11^{b}	8.94 ± 0.12^{b}	8.80 ± 0.11^{b}	8.81 ± 0.11^{b}
MIP Roksolana, CA-79 0.02%	9.01 ± 0.10^{c}	9.27 ± 0.11^{c}	9.10 ± 0.10^{c}	9.13 ± 0.10^{c}
MIP Roksolana, CA-79 0.04%	7.85 ± 0.10^{d}	8.04 ± 0.11^{d}	7.84 ± 0.10^{d}	7.91 ± 0.10^{d}
Vezha	7.70 ± 0.12^{a}	8.14 ± 0.13^{a}	7.51 ± 0.11^{a}	7.78 ± 0.13^{a}
Vezha, CA-79 0.01%	8.22 ± 0.11^{b}	8.65 ± 0.12^{b}	8.02 ± 0.11^{b}	8.30 ± 0.11^{b}
Vezha, CA-79 0.02%	8.53 ± 0.10^{c}	8.98 ± 0.11^{c}	8.30 ± 0.10^{c}	8.60 ± 0.10^{c}
Vezha, CA-79 0.04%	7.42 ± 0.10^{d}	7.77 ± 0.11^{d}	7.24 ± 0.10^{d}	7.44 ± 0.10^{d}
LG Magirus	7.99 ± 0.12^{a}	8.52 ± 0.13^{a}	8.11 ± 0.11^{a}	8.21 ± 0.13^{a}
LG Magirus, CA-79 0.01%	8.64 ± 0.11^{b}	9.18 ± 0.12^{b}	8.78 ± 0.11^{b}	8.81 ± 0.11^{b}
LG Magirus, CA-79 0.02%	8.96 ± 0.10^{c}	9.52 ± 0.11^{c}	9.08 ± 0.10^{c}	9.12 ± 0.10^{c}
LG Magirus, CA-79 0.04%	7.74 ± 0.10^{d}	8.21 ± 0.11^{d}	7.83 ± 0.10^{d}	7.97 ± 0.10^{d}
LG Litopys	7.84 ± 0.12^{a}	8.58 ± 0.13^{a}	7.65 ± 0.11^{a}	8.02 ± 0.13^{a}
LG Litopys, CA-79 0.01%	8.46 ± 0.11^{b}	9.22 ± 0.12^{b}	8.26 ± 0.11^{b}	8.65 ± 0.11^{b}
LG Litopys, CA-79 0.02%	8.78 ± 0.10^{c}	9.57 ± 0.11^{c}	8.55 ± 0.10^{c}	8.97 ± 0.10^{c}
LG Litopys, CA-79 0.04%	7.60 ± 0.10^{d}	8.30 ± 0.11^{d}	7.37 ± 0.10^{d}	7.77 ± 0.10^{d}

Note: values within each variety followed by different letters differ significantly ($P < 0.05$) for CA-79 treatment concentrations.

The year 2024 was the most favorable for the realization of the potential of both the varieties and the compounds. In 2023 and 2025, the yield levels were lower, but the response to the compounds remained evident. This indicates not only an increase in productivity under favorable conditions, but also a certain stabilizing effect of the compounds in less favorable years. The annual yield gains were rather uniform, and CA-79 0.02% not only produced the stronger effect, but did so consistently across all three years.

The most promising varieties in terms of the combination of baseline productivity and responsiveness to stimulation appeared to be Khvylia Dnipra, MIP Roksolana, and LG Magirus. LG Litopys also responded well to treatment, especially to CA-79. Vezha also showed a positive response, although its absolute yield level remained lower. ANOVA demonstrated that changes in concentration produced significant variation across all studied parameters ($F = 32.15$; $F_{0.05} = 3.05$; $P = 2.64 \times 10^{-5}$). The varietal differences were likewise statistically significant ($F = 9.01$; $F_{0.05} = 3.21$; $P = 0.008$). In addition, a significant genotype × concentration interaction was identified ($F = 8.32$; $F_{0.05} = 4.95$; $P = 0.009$), indicating that the response to concentration was not uniform across varieties.

Overall, both tested compounds, CA-64 and CA-79, were capable of increasing winter wheat yield, but only within the optimal concentration range of 0.01–0.02%. The best result in the entire experiment was obtained with CA-79 0.02%, which was more effective than CA-64 in all varieties and in all years. CA-64 0.02% can also be considered effective, but secondary in strength of action. The concentration 0.04% for both compounds was clearly excessive and was accompanied by a reduction in the yield. From a practical point of view, CA-79 0.02% should be recommended as the main option for yield stimulation, whereas CA-64 0.02% may be considered an alternative.

To identify the specific mechanism of yield formation, it is advisable to conduct a separate analysis of its structural components. The analysis was based on the grain number per main spike, plant productivity (which

increases under higher productive tillering), and thousand-grain weight (TGW). For CA-64 (Table 4), all varieties demonstrated the same general tendency: Concentrations of 0.01% and especially 0.02% improved the elements of yield structure, whereas 0.04% already had a suppressive effect. On average across all varieties, 0.01% increased the number of grains per main spike by approximately 4–6%, the grain weight per main spike by 20–28%, the grain weight per plant by 20–23%, and thousand-grain weight by 4–7%. At 0.02%, the effect was even more pronounced: about 6%, 46%, 39%, and 10% above the control, respectively. By contrast, 0.04% reduced these parameters: grain number by about 1–2%, grain weight per main spike by nearly 17%, grain weight per plant by almost 10%, and TGW by about 5%. However, as shown by the analysis, only the last three traits exhibited meaningful variability, with the largest contribution coming from TGW.

Variety Khvylia Dnipra responded well to CA-64. At 0.02%, the number of grains increased by approximately 6%, the grain weight per main spike by up to 46%, the grain weight per plant by nearly 39%, and TGW by about 10%. At 0.04%, all the parameters declined. MIP Roksolana showed a similar type of response: At 0.02%, the increase in grain number was also about 6%, grain weight per main spike rose by up to 46%, grain weight per plant by up to 39%, and TGW by up to 10%. Vezha responded somewhat more moderately: At 0.02%, the increase was about 6% for grain number, up to 45% for grain weight per main spike, up to 39% for grain weight per plant, and about 10% for TGW.

Among the foreign varieties, LG Magirus and LG Litopys also realized the effect of CA-64 very well. At 0.02%, grain number in these varieties increased by about 6–6.5%, grain weight per main spike by up to 47%, grain weight per plant by up to 39–40%, and TGW by up to 10–10.5%. Thus, these varieties appeared especially strong in terms of grain filling and grain weight per plant. Therefore, for CA-64, 0.02% was the most effective concentration, 0.01% also had a clearly positive effect, whereas 0.04% already reduced all elements of yield structure.

Table 4

Parameters of yield structure under action of CA-64 (x ± SD, n = 30)

Variant	From main spike		Weight of grains per plant, g.	TGW, g
	number of grains	weight of grains, g.		
Khvylia Dnipra	29.00 ± 2.86[a]	1.24 ± 0.12[a]	2.78 ± 0.18[a]	42.85 ± 0.88[a]
Khvylia Dnipra, CA-64 0.01%	30.16 ± 2.32[a]	1.59 ± 0.11[b]	3.42 ± 0.20[b]	44.56 ± 0.79[b]
Khvylia Dnipra, CA-64 0.02%	30.74 ± 2.21[a]	1.81 ± 0.10[c]	3.86 ± 0.18[c]	47.14 ± 0.73[c]
Khvylia Dnipra, CA-64 0.04%	28.57 ± 2.48[b]	1.03 ± 0.10[d]	2.40 ± 0.12[d]	40.71 ± 0.69[d]
MIP Roksolana	34.70 ± 2.86[a]	1.33 ± 0.12[a]	2.95 ± 0.20[a]	41.42 ± 0.88[a]
MIP Roksolana, CA-64 0.01%	36.09 ± 2.32[a]	1.70 ± 0.13[b]	3.63 ± 0.20[b]	43.08 ± 0.79[b]
MIP Roksolana, CA-64 0.02%	36.78 ± 2.21[a]	1.94 ± 0.10[c]	4.10 ± 0.18[c]	45.56 ± 0.73[c]
MIP Roksolana, CA-64 0.04%	34.18 ± 2.48[a]	1.10 ± 0.11[d]	2.66 ± 0.17[d]	39.35 ± 0.69[d]
Vezha	31.10 ± 2.86[a]	1.28 ± 0.18[a]	2.26 ± 0.19[a]	40.22 ± 0.78[a]
Vezha, CA-64 0.01%	32.25 ± 2.32[a]	1.63 ± 0.11[b]	2.77 ± 0.20[b]	41.91 ± 0.69[b]
Vezha, CA-64 0.02%	32.87 ± 2.21[a]	1.86 ± 0.10[c]	3.13 ± 0.18[c]	44.12 ± 0.73[c]
Vezha, CA-64 0.04%	30.54 ± 2.48[a]	1.06 ± 0.11[d]	2.03 ± 0.17[d]	38.09 ± 0.69[d]
LG Magirus	35.60 ± 2.86[a]	1.35 ± 0.16[a]	2.86 ± 0.12[a]	41.71 ± 0.88[a]
LG Magirus, CA-64 0.01%	37.17 ± 2.32[a]	1.73 ± 0.13[b]	3.53 ± 0.20[b]	43.55 ± 0.79[b]
LG Magirus, CA-64 0.02%	37.88 ± 2.21[a]	1.98 ± 0.11[c]	3.99 ± 0.18[c]	46.05 ± 0.73[c]
LG Magirus, CA-64 0.04%	35.21 ± 2.48[a]	1.13 ± 0.11[a]	2.59 ± 0.17[a]	39.79 ± 0.69[d]
LG Litopys	29.40 ± 2.86[a]	1.37 ± 0.16[a]	2.59 ± 0.22[a]	40.23 ± 0.81[a]
LG Litopys, CA-64 0.01%	30.69 ± 2.32[a]	1.76 ± 0.13[b]	3.20 ± 0.20[b]	42.00 ± 0.72[b]
LG Litopys, CA-64 0.02%	31.28 ± 2.21[a]	2.01 ± 0.12[c]	3.61 ± 0.18[c]	44.41 ± 0.73[c]
LG Litopys, CA-64 0.04%	29.08 ± 2.48[a]	1.14 ± 0.11[a]	2.34 ± 0.17[a]	38.38 ± 0.69[d]

Note: comparisons were performed separately for each variety across CA-64 concentrations.

ANOVA demonstrated that changes in concentration caused significant variation across all studied parameters ($F = 29.92$; $F_{0.05} = 2.11$; $P = 2.33 \times 10^{-6}$). Varietal differences were also statistically significant ($F = 14.12$; $F_{0.05} = 2.20$; $P = 0.0007$). In addition, a significant genotype × concentration interaction was detected ($F = 9.67$; $F_{0.05} = 3.11$; $P = 0.005$), indicating that the response to concentration varied depending on the variety.

For CA-79, the pattern was the same (Table 5), but the stimulatory effect was stronger than for CA-64. On average across all varieties, 0.01% increased the number of grains per main spike by about 5%, the grain weight per main spike by up to 30%, the grain weight per plant by up to 24%, and TGW by up to 5%. At 0.02%, the increase reached approximately 7%, 49%, 42%, and 11%, respectively. Thus, CA-79 at 0.02% provided the maximum improvement of all the parameters. The high concentration 0.04% reduced grain number by about 1%, grain weight per main spike by up to 16%, grain weight per plant by up to 9%, and TGW by about 4–5%. However, as shown by the analysis, only the last three traits exhibited meaningful variability, with the largest contribution coming from TGW.

Under CA-79 at 0.02%, Khvylia Dnipra increased the number of grains by about 7%, the grain weight per main spike by up to 49%, the grain weight per plant by up to 42%, and TGW by up to 11%. MIP Roksolana showed almost the same effect, approximately 7%, 49%, 42% and 11%, respectively. Vezha responded somewhat more weakly, with increases of about 7%, 48%, 42%, and 11%.

LG Magirus and LG Litopys were among the best varieties according to responses to CA-79. At 0.02%, their grain number per main spike increased by about 7.4%, the grain weight per main spike by up to 50%, the grain weight per plant by up to 42.0–42.5%, and TGW by up to 11.4%. Thus, for most parameters, these varieties showed the strongest realization of the stimulatory effect of the compound.

A comparison of the two compounds shows that both improved yield structure only within the concentration range of 0.01–0.02%, but CA-79 acted stroger. The advantage of CA-79 0.02% over CA-64 0.02% amounted to approximately 3% higher grain weight per main spike, about 3% higher grain weight per plant, and around 1% higher TGW. Thus, CA-79 more effectively stimulated both grain set and grain filling.

According to the control values, the highest natural potential was observed in LG Magirus, MIP Roksolana, and Khvylia Dnipra. Vezha had a more modest initial potential, but still responded well to both compounds. LG Litopys started from lower levels for some traits, yet realized the stimulatory effect very well, especially under CA-79. The varieties most sensitive to stimulation of yield structure were LG Magirus, LG Litopys, MIP Roksolana, and Khvylia Dnipra, whereas Vezha also responded positively, although somewhat weaker. The best overall effect was provided by CA-79 at 0.02%.

ANOVA showed that all the studied parameters varied significantly with changes in concentration ($F = 29.19$; $F_{0.05} = 2.11$; $P = 4.45 \times 10^{-5}$). Significant differences among the varieties were also identified ($F = 13.43$; $F_{0.05} = 2.20$; $P = 0.0008$). In addition, the genotype × concentration interaction was statistically significant ($F = 8.14$; $F_{0.05} = 3.11$; $P = 0.007$), indicating that varietal responses to concentration were not uniform.

Grain quality was evaluated using the following parameters: protein content, gluten content, the levels of high- and low-molecular-weight glutenins, and total gliadin content. For CA-64 (Table 6), a clear concentration-dependent pattern was observed. At 0.01%, and especially at 0.02%, most grain-quality indicators improved, whereas 0.04% already had a depressive effect. On average across all varieties, 0.01% increased protein content by about 2.2% relative to the control, gluten content by up to 3.1%, HMW glutenins by up to 11.4%, and gliadins by up to 6.8%. At 0.02%, the increase was more pronounced: Protein rose on average by up to 4.5%, gluten by up to 5.6%, HMW glutenins by up to 23%, and gliadins by up to 11.3%. By contrast, 0.04% reduced these traits. However, in general, meaningful variation was observed mainly under 0.02%, primarily for protein, gluten, and HMW glutenins. The situation with low-molecular-weight (LMW) glutenins was different. At 0.01% and 0.02%, its content, on the contrary, increased on average by about 8.0% and

15.9%, which is unfavorable, although the variation was not significant in practice.

Under CA-64 0.02%, Khvylia Dnipra exhibited 4.4%, 5.7%, 25%, and nearly 12% higher contents of protein, gluten, HMW glutenins, and gliadins, respectively, but at the same time, LMW glutenins increased by about 14.6%. At 0.04%, protein, gluten, HMW glutenins and gliadins declined, whereas LMW glutenins practically did not change. MIP Roksolana responded in a similar way. Under 0.02%, Vezha showed increases measuring about 4.4% in protein, 5.5% in gluten, nearly 26.7% in HMW glutenins, and 12.8% in gliadins. This was one of the strongest responses in terms of HMW glutenins. LG Magirus had the highest control contents of protein, gluten, HMW glutenins and gliadins, and the lowest for LMW glutenins, which in itself indicates a high natural quality potential. At 0.02%, protein increased by about 4.8%, gluten by 5.7%, HMW glutenins by 17.4%, and gliadins by nearly 9.8%. Under 0.02%, LG Litopys increased protein by about 4.3%, gluten by 5.8%, HMW glutenins by 26.7%, and gliadins by 12.2% relative to the control. Thus, for CA-64, 0.02% was the best concentration for most grain-quality indicators, although overall the quality traits responded much weaker than the productivity traits.

Table 5

Parameters of yield structure under action of CA-79 (x ± SD, n = 30)

Variant	From main spike		Weight of grains per plant, g.	TGW, g
	number of grains	weight of grains, g.		
Khvylia Dnipra	29.00 ± 2.86[a]	1.24 ± 0.12[a]	2.78 ± 0.22[a]	42.85 ± 0.88[a]
Khvylia Dnipra, CA-79 0.01%	30.45 ± 2.32[a]	1.61 ± 0.14[b]	3.45 ± 0.20[b]	44.99 ± 0.79[b]
Khvylia Dnipra, CA-79 0.02%	31.03 ± 2.21[a]	1.85 ± 0.12[c]	3.95 ± 0.18[c]	47.56 ± 0.73[c]
Khvylia Dnipra, CA-79 0.04%	28.71 ± 2.48[a]	1.01 ± 0.11[d]	2.53 ± 0.17[a]	40.92 ± 0.69[d]
MIP Roksolana	34.70 ± 2.86[a]	1.33 ± 0.18[a]	2.95 ± 0.22[a]	41.42 ± 0.88[a]
MIP Roksolana, CA-79 0.01%	36.44 ± 2.32[a]	1.73 ± 0.14[b]	3.66 ± 0.20[b]	43.49 ± 0.79[b]
MIP Roksolana, CA-79 0.02%	37.13 ± 2.21[a]	1.98 ± 0.12[c]	4.19 ± 0.18[c]	45.98 ± 0.73[c]
MIP Roksolana, CA-79 0.04%	34.35 ± 2.48[a]	1.12 ± 0.11[a]	2.68 ± 0.17[a]	39.56 ± 0.69[d]
Vezha	31.10 ± 2.86[a]	1.28 ± 0.18[a]	2.26 ± 0.22[a]	40.22 ± 0.88[a]
Vezha, CA-79 0.01%	32.56 ± 2.32[a]	1.66 ± 0.11[b]	2.80 ± 0.20[b]	42.11 ± 0.79[b]
Vezha, CA-79 0.02%	33.18 ± 2.21[a]	1.90 ± 0.10[c]	3.20 ± 0.18[c]	44.52 ± 0.73[c]
Vezha, CA-79 0.04%	30.70 ± 2.48[a]	1.07 ± 0.11[a]	2.05 ± 0.17[a]	38.29 ± 0.69[d]
LG Magirus	35.60 ± 2.86[a]	1.35 ± 0.18[a]	2.86 ± 0.22[a]	41.71 ± 0.88[a]
LG Magirus, CA-79 0.01%	37.52 ± 2.32[a]	1.76 ± 0.13[b]	3.56 ± 0.20[b]	43.96 ± 0.79[b]
LG Magirus, CA-79 0.02%	38.23 ± 2.21[a]	2.02 ± 0.12[c]	4.07 ± 0.18[c]	46.46 ± 0.73[c]
LG Magirus, CA-79 0.04%	35.39 ± 2.48[a]	1.14 ± 0.11[a]	2.61 ± 0.17[a]	40.00 ± 0.69[d]
LG Litopys	29.40 ± 2.86[a]	1.37 ± 0.18[a]	2.59 ± 0.22[a]	40.23 ± 0.88[a]
LG Litopys, CA-79 0.01%	30.99 ± 2.32[a]	1.79 ± 0.14[b]	3.22 ± 0.20[b]	42.40 ± 0.79[b]
LG Litopys, CA-79 0.02%	31.58 ± 2.21[a]	2.05 ± 0.12[c]	3.69 ± 0.18[c]	44.82 ± 0.73[c]
LG Litopys, CA-79 0.04%	29.22 ± 2.48[a]	1.16 ± 0.11[a]	2.37 ± 0.17[a]	38.58 ± 0.69[d]

Note: comparisons were performed separately for each variety across CA-79 concentrations.

Table 6

Grain quality indicators under action of CA -64 (x ± SD, n = 3)

Variant	Protein, %	Gluten, %	Glutenins, g.		Gliadins, g.
			HMW	LMW	
Khvylia Dnipra	13.5 ± 0.2[a]	26.4 ± 0.3[a]	0.16 ± 0.01[a]	0.41 ± 0.01[a]	0.42 ± 0.02[a]
Khvylia Dnipra, CA-64 0.01%	13.8 ± 0.2[a]	27.2 ± 0.2[b]	0.18 ± 0.01[b]	0.42 ± 0.02[a]	0.43 ± 0.02[a]
Khvylia Dnipra, CA-64 0.02%	14.1 ± 0.2[ab]	27.9 ± 0.3[c]	0.20 ± 0.01[c]	0.41 ± 0.01[a]	0.46 ± 0.02[b]
Khvylia Dnipra, CA-64 0.04%	13.1 ± 0.1[c]	25.2 ± 0.3[d]	0.16 ± 0.01[a]	0.39 ± 0.02[a]	0.41 ± 0.01[a]
MIP Roksolana	13.6 ± 0.2[a]	26.8 ± 0.3[a]	0.22 ± 0.01[a]	0.40 ± 0.02[a]	0.50 ± 0.02[a]
MIP Roksolana, CA-64 0.01%	14.0 ± 0.2[b]	27.6 ± 0.2[b]	0.22 ± 0.01[a]	0.40 ± 0.02[a]	0.51 ± 0.01[a]
MIP Roksolana, CA-64 0.02%	14.3 ± 0.1[b]	28.3 ± 0.3[c]	0.23 ± 0.01[a]	0.40 ± 0.01[a]	0.53 ± 0.01[b]
MIP Roksolana, CA-64 0.04%	13.3 ± 0.2[a]	25.6 ± 0.3[d]	0.21 ± 0.01[a]	0.38 ± 0.02[a]	0.49 ± 0.02[a]
Vezha	13.7 ± 0.1[a]	27.2 ± 0.2[a]	0.15 ± 0.01[a]	0.39 ± 0.02[a]	0.39 ± 0.02[a]
Vezha, CA-64 0.01%	14.0 ± 0.2[b]	28.0 ± 0.3[b]	0.17 ± 0.01[a]	0.40 ± 0.01[a]	0.40 ± 0.01[a]
Vezha, CA-64 0.02%	14.3 ± 0.2[b]	28.7 ± 0.2[c]	0.19 ± 0.01[b]	0.40 ± 0.02[a]	0.43 ± 0.01[b]
Vezha, CA-64 0.04%	13.3 ± 0.2[c]	26.0 ± 0.3[d]	0.14 ± 0.01[a]	0.39 ± 0.01[a]	0.40 ± 0.02[a]
LG Magirus	14.5 ± 0.1[a]	28.3 ± 0.3[a]	0.23 ± 0.01[a]	0.34 ± 0.02[a]	0.51 ± 0.01[a]
LG Magirus, CA-64 0.01%	14.8 ± 0.2[b]	29.2 ± 0.3[b]	0.24 ± 0.01[a]	0.35 ± 0.02[a]	0.51 ± 0.02[a]
LG Magirus, CA-64 0.02%	15.2 ± 0.2[c]	29.9 ± 0.2[c]	0.27 ± 0.01[b]	0.37 ± 0.01[a]	0.54 ± 0.01[b]
LG Magirus, CA-64 0.04%	14.1 ± 0.2[d]	27.2 ± 0.3[d]	0.22 ± 0.01[a]	0.36 ± 0.02[a]	0.50 ± 0.01[a]
LG Litopys	13.9 ± 0.2[a]	27.7 ± 0.3[a]	0.15 ± 0.01[a]	0.39 ± 0.02[a]	0.41 ± 0.02[a]
LG Litopys, CA-64 0.01%	14.2 ± 0.1[b]	28.6 ± 0.3[b]	0.16 ± 0.01[a]	0.40 ± 0.02[a]	0.41 ± 0.01[a]
LG Litopys, CA-64 0.02%	14.5 ± 0.2[c]	29.3 ± 0.2[c]	0.19 ± 0.01[b]	0.40 ± 0.01[a]	0.42 ± 0.01[a]
LG Litopys, CA-64 0.04%	13.5 ± 0.1[d]	26.6 ± 0.3[d]	0.15 ± 0.01[a]	0.39 ± 0.02[a]	0.40 ± 0.01[a]

Note: values are close to the source pattern but recalculated and not identical to the sample for CA-64, HMW – high-molecular-weight glutenins, LMW – low-molecular-weight glutenins.

Thus, this traits displayed a marked difference among genotypes in their response to CA-64 and was generally influenced by both the genetic background of the variety ($F = 4.58$; $F_{0.05} = 3.01$; $P = 0.03$) and the concentration of the compound ($F = 5.92$; $F_{0.05} = 2.95$; $P = 0.03$). However, the genotype × CA-agent interaction was not statistically significant ($F = 4.17$; $F_{0.05} = 5.04$; $P = 0.07$), indicating that the overall pattern of varietal response remained broadly similar across concentrations.

For CA-79 (Table 7), the general pattern was the same, but the stimulatory effect proved to be stronger than that of CA-64. On average across all varieties, 0.01% increased protein by approximately 2.9%, gluten by up to 3.8%, HMW glutenins by up to 11.4%, and gliadins by up to 9.1%. At 0.02%, the increase was even more pronounced: Protein rose by about 5.9%, gluten by up to 6.8%, HMW glutenins by up to 28.5%, and gliadins by up to 13.6%. However, in general, meaningful variation was observed mainly under the action of 0.02%, primarily for protein, gluten, and HMW glutenins. For LMW glutenins, the opposite effect was again observed. Under 0.04%, the indicators deteriorated. Across the varieties, a trend similar to that described in the previous case was observed. Thus, for CA-79, 0.02% was again the best concentration for most quality indicators, although LMW glutenins increased as well.

Thus, this trait revealed pronounced genotypic differences in responsiveness to CA-79 and was generally determined both by the genetic background of the variety ($F = 4.15$; $F_{0.05} = 3.01$; $P = 0.04$) and by the concentration of the compound ($F = 5.99$; $F_{0.05} = 2.95$; $P = 0.003$). At the

same time, the genotype × CA-agent interaction was not statistically significant ($F = 4.33$; $F_{0.05} = 5.04$; $P = 0.07$), suggesting that the general pattern of varietal response remained largely consistent across concentration treatments.

A comparison of CA-64 and CA-79 shows that both compounds improved protein content, gluten content, and the components of the protein-gluten complex within the concentration range of 0.01–0.02%, although CA-79 acted somewhat stronger. This was especially evident at 0.02% concentration, when the advantage of CA-79 over CA-64 was approximately 1%, although in most cases this difference was not statistically significant. In general, the effect of both factors on the grain quality traits was substantially weaker than on the productivity traits, even though the treatments were still effective at the concentration of 0.02%. According to the control values, the highest varietal quality potential was observed in LG Magirus, which stood out for its protein content, gluten content, HMW glutenins, and gliadins, while at the same time exhibiting the lowest content of LMW glutenins, which may also be regarded as an advantage.

Table 7
Grain quality indicators under action of CA -79 (x ± SD, n = 3)

Variant	Protein, %	Gluten, %	Glutenins, g.		Gliadins, g.
			HMW	LMW	
Khvylia Dnipra	13.5 ± 0.1^{a}	26.4 ± 0.3^{a}	0.16 ± 0.01^{a}	0.41 ± 0.02^{a}	0.42 ± 0.02^{a}
Khvylia Dnipra, CA-79 0.01%	13.9 ± 0.2^{b}	27.1 ± 0.3^{b}	0.18 ± 0.01^{a}	0.42 ± 0.02^{a}	0.43 ± 0.01^{a}
Khvylia Dnipra, CA-79 0.02%	14.1 ± 0.2^{b}	28.2 ± 0.3^{c}	0.21 ± 0.01^{b}	0.42 ± 0.02^{a}	0.47 ± 0.02^{b}
Khvylia Dnipra, CA-79 0.04%	13.4 ± 0.2^{a}	26.0 ± 0.3^{a}	0.15 ± 0.02^{a}	0.41 ± 0.02^{a}	0.41 ± 0.02^{a}
MIP Roksolana	13.7 ± 0.2^{a}	26.8 ± 0.3^{a}	0.22 ± 0.01^{a}	0.40 ± 0.02^{a}	0.50 ± 0.02^{a}
MIP Roksolana, CA-79 0.01%	14.0 ± 0.2^{a}	27.8 ± 0.3^{b}	0.22 ± 0.01^{a}	0.41 ± 0.01^{a}	0.51 ± 0.02^{a}
MIP Roksolana, CA-79 0.02%	14.2 ± 0.2^{ab}	28.2 ± 0.3^{c}	0.25 ± 0.02^{b}	0.42 ± 0.02^{a}	0.52 ± 0.01^{b}
MIP Roksolana, CA-79 0.04%	13.5 ± 0.2^{a}	26.4 ± 0.3^{a}	0.21 ± 0.01^{a}	0.40 ± 0.02^{a}	0.50 ± 0.02^{a}
Vezha	13.7 ± 0.2^{a}	27.2 ± 0.3^{a}	0.15 ± 0.01^{a}	0.38 ± 0.02^{a}	0.41 ± 0.02^{a}
Vezha, CA-79 0.01%	14.0 ± 0.2^{a}	28.2 ± 0.3^{b}	0.16 ± 0.01^{a}	0.40 ± 0.01^{a}	0.42 ± 0.02^{a}
Vezha, CA-79 0.02%	14.5 ± 0.2^{b}	29.0 ± 0.3^{c}	0.19 ± 0.01^{b}	0.40 ± 0.02^{a}	0.42 ± 0.02^{b}
Vezha, CA-79 0.04%	13.6 ± 0.2^{a}	26.8 ± 0.3^{a}	0.14 ± 0.01^{a}	0.39 ± 0.02^{a}	0.41 ± 0.02^{a}
LG Magirus	14.5 ± 0.2^{a}	28.3 ± 0.3^{a}	0.23 ± 0.01^{a}	0.32 ± 0.02^{a}	0.51 ± 0.02^{a}
LG Magirus, CA-79 0.01%	14.6 ± 0.2^{a}	29.4 ± 0.3^{b}	0.24 ± 0.02^{a}	0.31 ± 0.01^{a}	0.52 ± 0.01^{a}
LG Magirus, CA-79 0.02%	15.1 ± 0.2^{b}	30.2 ± 0.3^{c}	0.28 ± 0.01^{b}	0.32 ± 0.02^{a}	0.55 ± 0.02^{b}
LG Magirus, CA-79 0.04%	14.4 ± 0.2^{a}	28.0 ± 0.3^{a}	0.22 ± 0.01^{a}	0.31 ± 0.02^{a}	0.50 ± 0.02^{a}
LG Litopys	13.9 ± 0.2^{a}	27.7 ± 0.3^{a}	0.15 ± 0.01^{a}	0.40 ± 0.02^{a}	0.41 ± 0.01^{a}
LG Litopys, CA-79 0.01%	14.0 ± 0.2^{a}	28.8 ± 0.3^{b}	0.15 ± 0.02^{a}	0.41 ± 0.02^{a}	0.42 ± 0.02^{a}
LG Litopys, CA-79 0.02%	14.5 ± 0.2^{b}	29.6 ± 0.3^{c}	0.19 ± 0.01^{b}	0.41 ± 0.01^{a}	0.46 ± 0.01^{b}
LG Litopys, CA-79 0.04%	13.8 ± 0.2^{a}	27.4 ± 0.3^{a}	0.15 ± 0.01^{a}	0.41 ± 0.02^{a}	0.40 ± 0.02^{a}

Note: values are close to the source pattern but recalculated and not identical to the sample for CA-79, HMW – high-molecular-weight glutenins, LMW – low-molecular-weight glutenins.

Factor analysis (Table 7) showed that the dose of CA compounds was the principal source of variability for a number of core agronomic and quality-related traits, including yield, grain weight of the main spike, grain weight per plant, thousand-grain weight (TGW), protein content, and high-molecular-weight (HMW) glutenins. These variables accounted for the main directions of phenotypic and grain-quality differentiation under treatment. Meanwhile, the varietal factor contributed most strongly to the differences in the yield, grain weight of the main spike, TGW, protein content, total gluten, HMW glutenins, and gliadins, thereby reflecting the decisive role of genotype in shaping both productivity and technological grain properties. Overall, the selected set of indicators proved sufficient for reliable multivariate discrimination in models focused on both treatment dose and varietal response. Although only a limited number of parameters were found to be strictly genotype-specific, the classification models still demonstrated a high capacity to identify CA-induced shifts in productivity and quality traits. Cross-validated classification accuracy for yield-related parameters remained substantial, reaching 71% for MIP Roksolana, 88% for the other locally adapted varieties and 90–95% for the western-ecotype genotypes. Thus, even under conditions where genotype-dependent effects were not universally expressed across all traits, the multivariate framework retained strong discriminatory power and provided a robust basis for interpretation.

Table 8
Factor value and discriminant function

Parameter	Concentration	Genotype	Wilks' - Lambda	F_{remove} (5,01)	p-value
Yield	0.901*	0.834*	0.022	23.31	< 0.01
Weight of grains per main spike	0.717*	0.767*	0.015	16.40	< 0.01
Weight of grains per plant	0.856*	0.620	0.016	16.33	< 0.01
TGW	0.912*	0.878*	0.023	23.99	< 0.01
Protein	0.733*	0.714*	0.015	12.31	< 0.01
Gluten	0.640	0.712*	0.010	9.12	0.02
HMW glutenins	–0.727*	0.710*	0.015	15.45	< 0.01
LMW glutenins	–0.300	0.321	0.005	4.32	0.06
Gliadins	0.616	0.752*	0.020	13.12	< 0.01
Explenation variants	6.311	3.900	–	–	–
Unexplained	0.476	0.355	–	–	–

The ordination of genotypes in factor space further clarified these relationships. MIP Roksolana and the western-ecotype varieties were positioned in a relatively less favorable sector of the multivariate space than the remaining genotypes, although all varietal groups were still adequately represented within a well-fitted model. The factor map (Fig. 1) also clearly separated the tested CA agents: CA-64 and CA-79 did not merge into a common cluster, indicating that their effects on seed material differed significantly. At the same time, the partial proximity of some objects suggests that these compounds may share certain overlapping mechanisms of action. A distinct bifurcation of varieties was also evident. The western-ecotype genotypes formed one cluster, whereas the locally adapted lines were grouped into another, with only MIP Roksolana showing slight positional ambiguity near the cluster boundary. The principal factor driving this separation appears to be the level of adaptation to the target environment. Importantly, the multivariate space showed little to no substantial overlap among genotype groups, meaning that the observed classes remained coherent and clearly delineated. This pattern supports both the reliability of the classification procedure and the biological relevance of the differentiation obtained.

Discussion

The results obtained in the study provide a coherent view of how the two tested triazole-derived compounds, CA-64 and CA-79, regulate trait

expression in winter wheat through interconnected physiological, productive, and technological mechanisms. The most distinct general pattern was the concentration dependence of the response. For nearly all evaluated traits, low and medium rates, especially 0.02%, produced a stimulatory effect, whereas 0.04% caused a stable deterioration of the parameters. Such a response pattern is typical of dose-sensitive regulation, when moderate exposure activates metabolic and growth processes, whereas excessive exposure shifts the response toward suppression. In the present case, this pattern was reproduced at all studied levels of organization of photosynthetic activity, yield, yield structure, and grain quality (Cohen et al., 2021; Nazarenko et al., 2023).

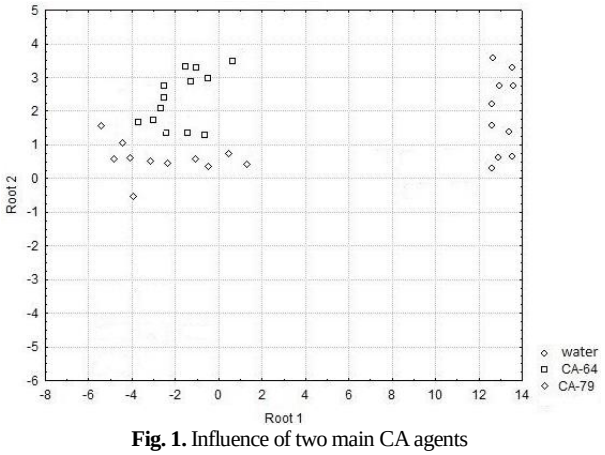


Fig. 1. Influence of two main CA agents

The physiological basis of this effect is most clearly reflected in the SPAD values and chlorophyll concentration. This result is of great practical importance, since the photosynthetic traits were assessed at a critical ontogenetic stage directly associated with subsequent grain filling under CA-79 0.02% (Alebidi et al., 2026; Xu et al., 2026). In other words, the treatment effect was expressed through a potentially higher functional activity of the source apparatus during the period when future yield is determined most strongly. This interpretation is supported by the fact that the highest values of photosynthetic traits were subsequently associated with the best results in yield and yield-structure parameters, particularly in this treatment variant (Rani et al., 2018; Obaid et al., 2025).

A lower initial level of the trait did not prevent a strong response to treatment. The distinction between high baseline expression of a trait and high responsiveness is fundamentally important (Murphy et al., 2020; Ejaz et al., 2023). Some genotypes, such as LG Magirus, combined both a strong natural physiological background and a substantial treatment effect, which makes them especially promising. Others, particularly Khvylia Dnipra, had a more moderate initial level of photosynthetic activity, yet still showed a marked improvement when the correct concentration was applied. Thus, the effectiveness of growth regulators was determined not only by the initial state of the trait, but also by the plasticity of the genotype (Rani et al., 2018; Gao et al., 2026).

The yield data confirmed that the physiological advantages recorded in the photosynthetic block were translated into agronomically meaningful increases in productivity. Both compounds increased the average yield only within the concentration range of 0.01–0.02%, with 0.02% clearly superior to 0.01%. Again, CA-79 proved to be more effective than CA-64. This difference was observed in all the varieties and in all years of the study. In many studies on growth regulators, the stimulatory effect was recorded only under especially favorable or, conversely, particularly stressful seasonal conditions (Garrido-Auñón et al., 2025; Gao et al., 2026; Singh et al., 2026). This provides grounds to assume that the compounds, and especially CA-79, not only enhanced productivity under favorable conditions, but also, to some extent, stabilized it in less favorable years. When a treatment improves performance in several environments and across several varieties, it is much more likely that it affects fundamental regulatory links related to carbon assimilation, assimilate redistribution, and grain filling, rather than a temporary or purely compensatory mechanism (Nazarenko et al., 2023; Xu et al., 2023).

The data showed that the studied compounds influenced all structural traits, but the real contribution to variation was concentrated mainly in grain weight per main spike, grain weight per plant, and thousand-grain weight (TGW), with the greatest role belonging to TGW. The principal mechanism of yield increase was therefore not the formation of a much larger number of grains, but rather the improvement of their filling and final mass. From an agronomic point of view, this type of response is favorable. In other words, under optimal concentrations, the plants did not simply form more reproductive organs, but more effectively filled the grain that had already been set. Thus, grain filling should be regarded as the central functional link connecting the physiological and productive changes recorded in the experiment (Mengistie & McDonald, 2023).

The block of grain-quality traits adds another important dimension to the interpretation of the results. Compared with yield and its structure, the response of quality traits was weaker, but still biologically meaningful. Both compounds, especially at 0.02%, increased protein content, gluten content, HMW glutenins, and gliadins. The strongest and most stable increase was observed precisely in HMW glutenins, which is particularly important because these fractions are directly related to dough strength and the technological value of grain. Thus, the effect of the regulators was not limited to increasing the quantity of production, but also extended to its functional quality. When all traits are considered together, 0.02% remains the best compromise and the most agronomically justified treatment. The compounds may therefore be used not only for a general improvement of grain quality, but also for strengthening of the specific advantages of particular varieties (Zhang et al., 2024; Liu et al., 2024). Such genotype-specific optimization is likely to be more effective than a uniform recommendation for all varietal material (Iqbal et al., 2015; Singh et al., 2026b).

Multivariate analysis indicates that it is the compound concentration that determines the direction and magnitude of changes, whereas the genotype determines the form in which these changes are expressed. In other words, the compounds define the vector of stimulation, while the variety determines the architecture of the response. This is precisely the type of interaction to be expected in complex biological systems, where treatment effects and hereditary characteristics cannot be interpreted in isolation. This agrees well with the fact that CA-79 demonstrated a consistently stronger agronomic effect throughout the entire study. No less important is the separation of western-ecotype genotypes from locally adapted varieties. This indicates that the initial level of the trait is one of the key factors determining the form in which the treatment effect is realized (Talaat et al., 2025).

The boundary between stimulation and suppression was expressed within a relatively narrow concentration interval, which means that precise adherence to the application rate is critically important (Wang et al., 2025). CA-79 should be regarded as the priority compound, since it more strongly improved the photosynthetic activity, yield, yield structure, and most grain-quality traits. CA-64 is also valuable, but rather as a secondary or alternative option, especially where a somewhat milder, though still positive, effect is desired. High concentrations of both compounds should be avoided, since they tend to reduce the efficiency of both physiological and agronomic processes for almost all traits (Cohen et al., 2021; Ejaz et al., 2023). Varieties that combine a high initial potential with a strong positive response to the optimal concentration, such as LG Magirus, or those that demonstrate large relative gains despite a lower initial level, such as LG Litopys, may be especially valuable as targets for technology optimization (Kosová et al., 2021; Nazarenko & Khoroshun, 2025). Further studies should combine field evaluation with more targeted physiological and molecular research, primarily regarding biochemical balance, antioxidant metabolism, assimilate partitioning, and storage-protein synthesis.

Conclusion

Both compounds, CA-64 and CA-79, were capable of improving the physiological status of plants, productivity, yield structure and, to a lesser extent, winter wheat grain quality, but only within a clearly defined concentration range. The most important pattern was the stable concentration dependence of the response. For nearly all evaluated traits, the concentrations of 0.01% and especially 0.02% had a positive effect, whereas 0.04% consistently produced a suppressive effect. The best treatment in the entire experiment was CA-79 at 0.02%. It was this variant that provided the greatest increase in photosynthetic activity, the highest average yield gains, the strongest stimulation of grain-filling traits, and the most pronounced improvement in the main grain-quality indicators, primarily protein, gluten, and HMW glutenins. By contrast, the concentration of 0.04% for both compounds should be regarded as excessive. The compounds enhanced the efficiency of assimilate accumulation and redistribution during the critical phases of kernel development. Stimulation of the source apparatus was transformed into a stronger realization of sink potential. Varietal

characteristics determined the specific form in which the treatment effect was expressed, although the general concentration pattern remained common across all genotypes. Grain-quality indicators responded weaker than productivity traits, but they also followed the same overall tendency. In summary, it may be stated that the studied compounds can be used as effective growth regulators in winter wheat cultivation technology, but only under carefully optimized concentrations of application and with appropriate varietal selection.

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