



## Estimation of effectivity of new growth regulators on winter wheat productivity and quality

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Triazole derivatives are powerful agronomic tools that regulate multiple plant processes. In wheat, they help balance vegetative and reproductive growth, enhance tolerance to abiotic and biotic stresses, and support stable, high yields with improved grain quality. Their dual functionality as growth regulators and broad-spectrum fungicides enables integrated, resource-efficient programs that couple crop protection with physiological stimulation. In this study, seeds from five winter wheat varieties (1,000 grains per treatment) were primed in aqueous solutions of two triazole-type compounds, CA-64 and CA-79, at 0.01%, 0.02% and 0.04%. Soaking lasted 24 hours under standard protocols for plant growth stimulants; water-soaked seeds served as controls. Triazole-based seed priming is increasingly used to fine-tune early crop physiology, yet concentration-response windows and genotype specificity remain underdefined for winter wheat. Two triazole agents have been evaluated across varieties and measurement systems and a narrow, repeatable stimulatory window was found at 0.01–0.02% with a consistent toxicity threshold at 0.04%. Within the effective range, CA-79 outperformed CA-64 for photosynthetic status (SPAD and calculated chlorophyll), grain yield, yield components (grain weight per main spike, total grain weight per plant, thousand-grain weight (TGW) and grain quality). Responses were robust across years and genotypes, with the largest advantage of CA-79 at 0.02%, particularly in MIP Feeriya and the western ecotypes (MV Nador, MV Menrot), while still conferring clear gains in local varieties (Pozitsia Odeska, Tenor). CA-79 (0.02%) reliably increased protein and wet gluten and shifted the glutenin profile toward higher HMW fractions without inflating LMW glutenins, which was an advantageous pattern for baking strength. CA-64 at 0.02% was a safe, positive alternative, though the magnitude of improvement was generally smaller. At 0.04%, both agents depressed photosynthetic indicators, yield, and quality indices; HMW glutenins declined most, underscoring a clear toxicity boundary that should be avoided. Genotype conditioning was evident. Local genotypes showed predictable uplift at 0.02% (CA-79 preferred, CA-64 dependable as fallback). Western ecotypes benefited at 0.01–0.02%, with CA-79 providing a broader margin; doses above 0.02% are not recommended. Operationally, CA-79 at 0.02% is the default choice for maximal, balanced improvements in photosynthetic capacity, yield, and baking quality. Where risk aversion or seed-lot sensitivity warrants caution, 0.01% offers a gentler yet significant uplift. CA-64 (0.01–0.02%) remains a practical second line when access or regulatory status limits CA-79. 0.04% should be avoided for both compounds. These findings delineate concentration-genotype operating zones for triazole priming in winter wheat and highlight CA-79 as the leading option at 0.02% concentration. Ongoing work will extend the assessment to micronutrient enrichment (Fe, Zn, Cu, Mn) to link physiological stimulation with nutritional quality gains.

**Keywords:** cereals; variety; triazole; yield; winter wheat; grain quality; photosynthetic activity.

### Introduction

Ensuring stable grain production is a strategic task for most countries worldwide, since cereals form the basis of human nutrition and the feed base of livestock. Among them, wheat (*Triticum aestivum* L.) holds a leading position in sown area and production volume. However, yield and grain quality potential are far from always realized under production conditions due to environmental stress factors, nutrient deficiencies, drought, lodging, disease damage, and more. Under such conditions, plant growth regulators, synthetic and natural substances capable of influencing growth, development and yield formation, become especially important (Roostaei et al., 2018; Nazarenko et al., 2019).

Growth regulators are biologically active compounds that act at low concentrations and modify physiological and biochemical processes in plants. They can mimic or inhibit the action of natural phytohormones, including auxins, cytokinins, gibberellins, abscisic acid, and ethylene. Among modern groups, those of greatest significance for cereals include: triazole regulators (paclobutrazol, uniconazole, tebuconazole, triadimenol), which reduce stem height, prevent lodging, increase lignin content, and improve water use; products based on humic and fulvic acids, which stimulate root system development and improve nutrient availability; amino acid and peptide complexes, which reduce the effects of abiotic stresses and enhance photosynthesis; and epigenetically active compounds, which help shape adaptive responses at the level of gene expression. Owing to these properties,

plant growth regulators are viewed as tools for ecologically sound, intensified crop production (Roostaei et al., 2018; Khalil et al., 2021; Wang et al., 2022). Wheat is highly demanding with respect to growing conditions. Its yield depends greatly on resistance to lodging, drought, and diseases, as well as on the efficient formation of yield components (number of productive stems, spike length, grain number and grain fullness). Growth regulators make it possible to influence these parameters. *Improving resistance to lodging.* Triazole products shorten internodes and strengthen cell walls by increasing lignin and cellulose content. This reduces the risk of yield losses during strong winds and heavy rains. *Optimizing photosynthetic activity.* Regulators can increase leaf area, chlorophyll concentration, and the duration of photosynthetic activity. As a result, plants capture light energy more effectively and produce more carbohydrates that are directed to grain filling (Peng et al., 2025).

The use of humic preparations and amino acid complexes stimulates the development of a deeper, more branched root system, which increases the efficiency of water and mineral nutrient uptake. Under high temperatures, drought, or salinity, plant growth regulators activate antioxidant enzymes (superoxide dismutase, catalase), stabilize cell membranes, and promote the accumulation of osmotically active substances (proline, sugars). It has been shown that certain regulators increase the protein and gluten content of grain, which is critical for the baking quality of wheat (Zhang et al., 2020; Zhao et al., 2025).

Research in Ukraine and abroad confirms that the application of triazole regulators can increase wheat yield by 10–20% depending on

the variety and seasonal conditions. For example, experiments with paclobutrazol have shown a 70–80% reduction in lodging and 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 (Singh et al., 2022; Obaid et al., 2025).

The application of humic substances in the Steppe zone of Ukraine has promoted better drought tolerance, thereby raising yields even in years with low precipitation. Similar results have been noted for barley and maize. The use of growth regulators offers a number of additional advantages. By increasing the efficiency of nitrogen and water use, the need for high fertilizer rates and irrigation can be reduced. In years with unfavorable weather, regulators help avoid significant losses. Most modern plant growth regulators are applied at very low doses (0.01–0.1%), which does not lead to hazardous accumulation in soil or produce (Shaki et al., 2022; Jiang, et al., 2023).

Despite the obvious advantages, widespread adoption of growth regulators in agriculture is constrained by several factors: insufficient awareness among farmers regarding optimal doses and application timing; the need for variety-specific studies, since different wheat genotypes respond differently to the same substances; and the lack of appropriate government support and programs to implement modern biotechnologies on small and medium-sized farms. However, current trends in agronomy indicate that the role of growth regulators will continue to grow. A particularly promising direction is the creation of combined products that unite regulators with micronutrients, biostimulants, and microbial inoculants (Zhang et al., 2020).

The application of growth regulators is an important element of agricultural intensification aimed at increasing the yield and quality of cereal crops, particularly wheat. They provide a comprehensive effect, from enhancing resistance to stress factors and preventing lodging to improving photosynthesis, root nutrition, and the baking properties of grain. Under conditions of climate change, limited water and mineral resources, and rising demand for high-quality food products, growth regulators are becoming an indispensable tool for sustainable production (Wang et al., 2022).

The study aimed to evaluate the potential of two new substances CA-64 (potassium [1,2,4]triazolo[1,5-c]quinazoline-2-thiolate), CA-79 (potassium tetrazolo[1,5-c]quinazoline-5-thiolate) as regulators of plant growth, investigate their ability to increase winter wheat productivity and photosynthetic activity, their action on different winter wheat modern varieties for improvement grain qualities. The key objectives were yield, yield structure and grain quality traits.

## Materials and methods

Field work took place in 2023–2025 on the experimental plots of the Department of Breeding and Seedfarming, Dnipro State Agrarian and Economic University, under steppe conditions with a sub-humid regime. For each treatment (and its water control), 1,000 bread-wheat seeds were primed for 24 h in aqueous solutions of two triazole-type compounds: CA-64 (potassium [1,2,4]triazolo[1,5-c]quinazoline-2-thiolate), CA-79 (potassium tetrazolo[1,5-c]quinazoline-5-thiolate). Each active ingredient was tested at 0.01%, 0.02%, and 0.04%. Dose choices followed prior cereal work with related chemistries (Nazaren-

ko et al., 2022). Crossing the variety panel with eight seed-treatment options (two compounds × three concentrations plus a water control) yielded 40 treatment–variety combinations.

The varietal set comprised domestically bred cultivars (e.g., Pozitsia Odeska, MIP Feeriya, Tenor) alongside western-ecotype entries (e.g., MV Nador, MV Menrot). Throughout the season we recorded phenology and, at heading, quantified leaf greenness with a SPAD-502 meter. Chlorophyll concentration (a+b) was then calculated from SPAD readings using the accepted relation  $Chl = 10M^{0.265}$  (Vesali et al., 2017), where M denotes SPAD units (Vesali et al., 2017). Each variant was sown in a plot of 10 m<sup>2</sup> with 0.15 m inter-row spacing and 6.5 m row length. The experimental test plots were laid out in a regular arrangement with a three-replicate sowing scheme, each plot having an area of 10 m<sup>2</sup>; the standard (control) was sown once per experiment. The seeding rate varied depending on the specified thousand-grain weight (hereinafter, TGW). Structural (yield-component) analysis was performed by measuring and threshing 25–30 well-developed plants, determining parameters such as the percentage of grain in total productivity, plant height, the weight and number of grains from the main spike, grain weight per plant, and thousand-grain weight (TGW). Protein content was determined using a Spektran-119R instrument (for protein and gluten determination; sample weight 10 g). Crop protection followed best practices for the sub-humid steppe zone to avoid confounding by unmanaged pests and diseases.

To interrogate multivariate structure and the diagnostic value of candidate traits, we applied linear discriminant analysis (LDA). This provided trait loadings identifying variables with the highest separation power among compound–dose classes and cross-validated classification accuracies useful for operational decisions (i.e., which priming regimes most reliably shift targeted phenotypes). In this way, measurements spanning seed-stage responses, winter-survival physiology, and in-season photosynthetic status were integrated into a single decision framework for triazole-based priming under regional conditions.

All statistics were run in Statistica 10.0 (TIBCO, Palo Alto, USA). We fit factorial ANOVA models with fixed effects of genotype (variety), compound identity, and concentration, including their interactions. Normality was checked via the Shapiro–Wilk W-test; where assumptions were not met, we used appropriate transformations or distribution-aware options. Descriptive summaries (means ± SD) were generated for every trait, and results were visualized to emphasize treatment patterns. When ANOVA terms were significant at  $P < 0.05$ , group means were separated using Tukey’s HSD.

## Results

To characterize the depressive impact, photosynthetic activity was assessed during a later critical growth stage (the period of main spike formation) (Table 1). Overall, the variability of this parameter was greater among domestic varieties than among foreign ones, which in some cases obscured statistically significant trends in its decrease or stimulation across triazole concentrations. Nonetheless, foreign cultivars generally demonstrated a higher photosynthetic capacity due to their genetic potential. This fact complicates interpretation, as the overall variability of the trait remains relatively low across all genotypes.

**Table 1**  
Analysis of photosynthetic activity under action of CA ( $x \pm SD$ ,  $n = 5$ )

Variant	Soil plant analysis development (SPAD)	Chl, $\mu\text{mol}/\text{cm}^2$	Variant	Soil plant analysis development (SPAD)	Chl, $\mu\text{mol}/\text{cm}^2$
Pozitsia Odeska	48.20 ± 1.34 <sup>a</sup>	620.29 ± 12.04	Pozitsia Odeska	48.20 ± 1.34 <sup>a</sup>	620.29 ± 12.04
Pozitsia Odeska, CA-64 0.01%	52.98 ± 1.41 <sup>b</sup>	730.21 ± 12.45	Pozitsia Odeska, CA-79 0.01%	53.87 ± 1.34 <sup>b</sup>	751.83 ± 12.04
Pozitsia Odeska, CA-64 0.02%	57.16 ± 1.32 <sup>c</sup>	834.95 ± 11.92	Pozitsia Odeska, CA-79 0.02%	58.55 ± 1.30 <sup>c</sup>	871.61 ± 11.80
Pozitsia Odeska, CA-64 0.04%	44.10 ± 1.36 <sup>d</sup>	534.04 ± 12.16	Pozitsia Odeska, CA-79 0.04%	45.10 ± 1.34 <sup>d</sup>	554.41 ± 12.04
MIP Feeriya	47.12 ± 1.23 <sup>a</sup>	596.86 ± 11.39	MIP Feeriya	47.12 ± 1.23 <sup>a</sup>	596.86 ± 11.39
MIP Feeriya, CA-64 0.01%	51.08 ± 1.33 <sup>b</sup>	685.28 ± 11.98	MIP Feeriya, CA-79 0.01%	52.44 ± 1.31 <sup>b</sup>	717.28 ± 11.86
MIP Feeriya, CA-64 0.02%	56.18 ± 1.27 <sup>c</sup>	809.65 ± 11.62	MIP Feeriya, CA-79 0.02%	57.38 ± 1.20 <sup>c</sup>	840.69 ± 11.21
MIP Feeriya, CA-64 0.04%	43.49 ± 1.24 <sup>d</sup>	521.82 ± 11.45	MIP Feeriya, CA-79 0.04%	44.11 ± 1.22 <sup>d</sup>	534.24 ± 11.33
Tenor	48.09 ± 1.32 <sup>a</sup>	617.88 ± 11.92	Tenor	48.09 ± 1.32 <sup>a</sup>	617.88 ± 11.92
Tenor, CA-64 0.01%	51.87 ± 1.31 <sup>b</sup>	703.77 ± 11.86	Tenor, CA-79 0.01%	52.96 ± 1.22 <sup>b</sup>	729.73 ± 11.33
Tenor, CA-64 0.02%	55.39 ± 1.30 <sup>c</sup>	789.60 ± 11.80	Tenor, CA-79 0.02%	56.88 ± 1.20 <sup>c</sup>	827.67 ± 11.21
Tenor, CA-64 0.04%	45.12 ± 1.24 <sup>d</sup>	554.82 ± 11.45	Tenor, CA-79 0.04%	46.10 ± 1.22 <sup>d</sup>	575.20 ± 11.33

Variant	Soil plant analysis development (SPAD)	Chl, $\mu\text{mol}/\text{cm}^2$	Variant	Soil plant analysis development (SPAD)	Chl, $\mu\text{mol}/\text{cm}^2$
MV Nador	54.23 $\pm$ 0.94 <sup>a</sup>	760.68 $\pm$ 9.63	MV Nador,	54.23 $\pm$ 0.94 <sup>a</sup>	760.68 $\pm$ 9.63
MV Nador, CA-64 0.01%	58.11 $\pm$ 1.00 <sup>b</sup>	859.90 $\pm$ 10.00	MV Nador, CA-79 0.01%	58.98 $\pm$ 1.01 <sup>b</sup>	883.14 $\pm$ 10.06
MV Nador, CA-64 0.02%	62.95 $\pm$ 0.99 <sup>c</sup>	993.86 $\pm$ 9.94	MV Nador, CA-79 0.02%	64.15 $\pm$ 0.95 <sup>c</sup>	1028.87 $\pm$ 9.69
MV Nador, CA-64 0.04%	49.11 $\pm$ 0.96 <sup>d</sup>	640.42 $\pm$ 9.76	MV Nador, CA-79 0.04%	50.16 $\pm$ 0.91 <sup>d</sup>	664.12 $\pm$ 9.45
MV Menrot	54.97 $\pm$ 0.98 <sup>a</sup>	779.05 $\pm$ 9.88	MV Menrot	54.97 $\pm$ 0.98 <sup>a</sup>	779.05 $\pm$ 9.88
MV Menrot, CA-64 0.01%	58.99 $\pm$ 1.16 <sup>b</sup>	883.40 $\pm$ 10.97	MV Menrot, CA-79 0.01%	59.53 $\pm$ 1.15 <sup>b</sup>	898.01 $\pm$ 10.91
MV Menrot, CA-64 0.02%	63.45 $\pm$ 0.99 <sup>c</sup>	1008.36 $\pm$ 9.94	MV Menrot, CA-79 0.02%	64.95 $\pm$ 0.92 <sup>c</sup>	1052.62 $\pm$ 9.51
MV Menrot, CA-64 0.04%	49.90 $\pm$ 0.98 <sup>d</sup>	658.20 $\pm$ 9.88	MV Menrot, CA-79 0.04%	50.96 $\pm$ 0.94 <sup>d</sup>	682.50 $\pm$ 9.63

Note: significant differences at  $P < 0.05$  by factor analyse; comparison in terms of one variety.

Dose response is consistent for all varieties. 0.01% raises SPAD/Chl above control value, 0.02% is the peak, 0.04% depresses both traits below control in every variety. CA-79 outperforms CA-64 at the same concentrations (both SPAD and Chl), across all genotypes. Baselines differ by origin, locals (Pozitsia Odeska, MIP Feeriya, Tenor) start lower; western ecotypes (MV Nador, MV Menrot) start higher yet still gain strongly at 0.02%.

As for variety, SPAD/Chl of Pozitsia Odeska under CA-64 at 0.01% rose to 53.0/730; at 0.02% it rose to 57.2/835 (+19% SPAD, +35% Chl vs control); at 0.04% it fell to 44.1/534. For CA-79 at 0.01%, it rose to 53.9/752; at 0.02% it rose to 58.6/872 (+22%/+41% in comparison with control); at 0.04% it decreased to 45.1/554. SPAD/Chl of MIP Feeriya treated with CA-64 at 0.01% rose to 51.1/685, at 0.02% it peaked at 56.2/810 (+19%/+36%), at 0.04% it decreased to 43.5/522. For CA-79 at 0.01%, it rose to 52.4/717, at 0.02% it peaked at 56.9/841 (+21%/+41%), at 0.04% it fell to 44.1/534. Variety Tenor demonstrated the same situation under CA-64, at 0.01% it rose to 51.9/704, at 0.02% it peaked at 55.4/790 (+15%/+28%); at 0.04%, it decreased to 45.1/555. At CA-79 0.01% it rose to 53.0/730, at 0.02% it rose to 56.9/828 (+18%/+34%), at 0.04% it fell to 46.1/575. Gains were somewhat smaller than in Pozitsia/MIP. In general the best result was at 0.02%. CA-79 was more effective in action than CA-64; 0.04% should be avoided.

For MV Nador (western ecotype) there was a higher baseline in control, than for previous genotypes. Under action of CA-64 at 0.01% SPAD/Chl rose to 58.1/860, at 0.02% is rose to 63.0/994 (+16%/+31%), at 0.04%, it decreased to 49.1/640. For CA-79 at 0.01%, SPAD/Chl rose to 59.0/883, at 0.02% peaked at 64.2/1029 (+18%/+35%), at 0.04% fell to 50.2/664. MV Menrot (western ecotype) had the highest baseline in control, under action of CA-64 at 0.01% SPAD/Chl rose to 59.0/883, at 0.02%, it peaked at 63.5/1008 (+16%/+29%), at 0.04%, it fell to 49.9/658. Under action of CA-79 at 0.01%, it rose to 59.5/898; at 0.02% it rose to 65.0/1053 (+18%/+35%), at 0.04%, it fell to 51.0/683. For these varieties, there was a strong response at 0.02%, CA-79 was the best variant in treatment, while 0.04% was clearly detrimental.

Across all varieties, CA-79 0.02% > CA-64 0.02% by 1–1.5 SPAD units and 25–40 Chl concentration units on average. The depressant effect at 0.04% was also slightly less severe with CA-79 than CA-64, but both were below control and not advisable.

Optimal operational dose for agriculture practice was 0.02% (reliable peak for photosynthetic status), 0.01% was a gentle, safer uplift, suitable for a risk-averse approach. CA-79 at 0.02% is preferable for the strongest enhancement, CA-64 is a good second choice (depends on individual genotype reaction), while 0.04% should be avoided for both agents (consistent reductions below water control values). Local varieties gained predictably and kept parity; western ecotypes, despite higher baselines, still achieve the highest absolute SPAD/Chl at CA-79 0.02%.

Thus, this trait showed a substantial difference between genotypes in the responsiveness of the CA and generally depended on the genotype of the original variety ( $F = 9.11$ ;  $F_{0.05} = 2.45$ ;  $P = 0.007$ ) and concentration of CA ( $F = 12.34$ ;  $F_{0.05} = 2.11$ ;  $P = 0.001$ ). This trait is important for characterizing the effect at a critical phase of the plants in ontogenesis for grain yield formation. A statistically significant genotype  $\times$  CA-agent interaction was developed too ( $F = 5.11$ ;  $F_{0.05} = 4.74$ ;  $P = 0.04$ ).

The effect of triazole-type substances has been manifested on the grain yield of winter wheat varieties. The data concerning this param-

eter is provided by varieties and concentrations in Table 2 and 3 (for CA-64 and CA-79 respectively) during 2023–2025 growing seasons.

As for CA-64 (Table 2) 0.02% is the peak every year and for the entire period on average, 0.01% gives a smaller but significant uplift, 0.04% is consistently depressing, below water control. The rank order by year is stable 0.02% > 0.01% > control > 0.04%. By variety, Pozitsia Odeska at 0.01% yielded 8.64 (+0.38, +4.6%), at 0.02% it yielded 8.91 (+0.65, +7.9%), at 0.04% yield fell to 7.92 – 0.34% – 4.1%. MIP Feeriya at 0.01% yielded 8.50 (+0.33, +4.0%), at 0.02% yield was 8.78 (+0.61, +7.5%), 0.04% yield fell to 7.85 (–0.32, –3.9%). Tenor at 0.01% yielded 8.10 (+0.32, +4.1%), at 0.02% 8.36 (+0.58, +7.5%), at 0.04% it yielded 7.57 (–0.21, –2.7%). Slightly smaller absolute gains than the others, but same ranking. For all varieties in 2023–2025, 0.02% always gave the top yield. For western ecotype MV Nador at 0.01% average yield was 8.58 (+0.37, +4.5%), at 0.02%, it was 8.91 (+0.70, +8.5%), at 0.04% yield fell to 7.90 (–0.31, –3.8%). MV Menrot at 0.01% yielded 8.31 (+0.31, +3.9%), at 0.02% 8.68 (+0.68, +8.5%), 0.04% yield fell to 7.84 (–0.16, –2.0%). Nador had the largest proportional gain at 0.02% among the varieties, while 0.04% was consistently harmful.

In 2023, 2024 and 2025, each variety shows the same monotonic pattern (0.02 > 0.01 > control > 0.04), confirming high robustness across seasons. In general for winter wheat agrotechnology 0.02% CA-64 is the operational optimum for yield across all five varieties, 0.01% is a conservative, still-beneficial option if risk or regulatory limits dictate, while 0.04% should be avoided. One should expect a roughly +7–9% yield lift at 0.02% and +4% at 0.01% (variety-dependent).

ANOVA-analysis confirmed a significant variability in all parameters with changing concentrations ( $F = 21.44$ ;  $F_{0.05} = 3.05$ ;  $P = 3.97 \times 10^{-4}$ ). Significant differences by varieties were also detected ( $F = 7.17$ ;  $F_{0.05} = 3.21$ ;  $P = 0.009$ ). A statistically significant genotype  $\times$  concentration interaction was developed too ( $F = 7.08$ ;  $F_{0.05} = 4.95$ ;  $P = 0.02$ ).

As for CA-79 (Table 3) concentration ranking is stable in every variety and year: 0.02% > 0.01% > control > 0.04%. 0.02% delivers the top yield, 0.01% gives a smaller but significant uplift, 0.04% is consistently depressing. By variety, Pozitsia Odeska at 0.01% yielded 8.82 (+0.56, +6.8%), 0.02% 9.16 (+0.90, +10.9%), falling at 0.04% to 7.85 (–0.41, –5.0%). MIP Feeriya at 0.01% yielded on average 8.68 (+0.51, +6.2%), at 0.02% yield was 9.03 (+0.86, +10.5%), at 0.04% yield fell to 7.79 (–0.38, –4.7%). Tenor at 0.01% yielded 8.29 (+0.51, +6.6%), at 0.02% yield was 8.62 (+0.84, +10.8%), at 0.04% it fell to 7.55 (–0.23, –3.0%). There was a clean monotonic response each year, 0.02% was the best. MV Nador at 0.01% yielded 8.74 (+0.53, +6.5%), at 0.02% yield was 9.09 (+0.88, +10.7%), at 0.04% yield fell to 7.80 (–0.41%, –5.0%). MV Menrot at 0.01% yielded 8.48 (+0.48, +6.0%), at 0.02% yield was 8.96 (+0.96, +12.0%), at 0.04% yield fell to 7.74 (–0.26%, –3.3%). The highest largest proportional lifts were at 0.02%.

In 2023, 2024, 2025, every variety follows the same monotone concentration – response, reinforcing reliability of the 0.02% optimum and the toxicity at 0.04%. In general for winter wheat agrotechnology CA-79 at 0.02% gave the operational optimum for yield across all varieties. 0.01% is a safer, still-beneficial fallback (+6% – 7% typical), while 0.04% is to be universally avoided (–3% to –5% vs. control). One should expect roughly +10–12% at 0.02% and +6–7% at 0.01%, variety-dependent. ANOVA-analysis confirmed a significant variability in all parameters with changing concentrations ( $F = 27.42$ ;  $F_{0.05} = 3.05$ ;  $P = 1.54 \times 10^{-5}$ ). Significant differences by

varieties were also detected ( $F = 8.89$ ;  $F_{0.05} = 3.21$ ;  $P = 0.007$ ). A statistically significant genotype  $\times$  concentration interaction was developed too ( $F = 8.01$ ;  $F_{0.05} = 4.95$ ;  $P = 0.01$ ).

Both triazoles show a clear stimulatory window at 0.01–0.02%, but CA-79 is the stronger and more consistent yield promoter across years and varieties. CA-64 gives reliable gains, yet the magnitude is typically a little lower than with CA-79. For both agents, 0.02% is the operational optimum giving a rise of +8–12% in comparison with control. 0.01% delivers a smaller, but still significant uplift +5–7%.

0.04% depresses yield for both compounds and should be avoided. The general recommendation is to use CA-79 at 0.02% for maximum, stable yield response, and adopt 0.01% where risk-aversion or seed lot sensitivity is a concern. One should not use 0.04% of either compound (consistent yield penalties). Local varieties (Pozitsia Odeska, MIP Feeriya, Tenor) respond predictably to 0.02% of either agent, western ecotypes (MV Nador, MV Menrot) also benefit, but one should keep to  $\leq 0.02\%$ .

**Table 2**  
Yield of winter wheat varieties under the action of CA-64 ( $\bar{x} \pm SD$ ,  $n = 9$ )

Variant	Yield, t/ha			
	2023	2024	2025	average
Pozitsia Odeska	8.24 $\pm$ 0.11 <sup>a</sup>	8.63 $\pm$ 0.12 <sup>a</sup>	7.90 $\pm$ 0.11 <sup>a</sup>	8.26 $\pm$ 0.14 <sup>a</sup>
Pozitsia Odeska, CA-64 0.01%	8.67 $\pm$ 0.12 <sup>b</sup>	8.94 $\pm$ 0.12 <sup>b</sup>	8.31 $\pm$ 0.13 <sup>b</sup>	8.64 $\pm$ 0.12 <sup>b</sup>
Pozitsia Odeska, CA-64 0.02%	8.99 $\pm$ 0.11 <sup>c</sup>	9.24 $\pm$ 0.12 <sup>c</sup>	8.51 $\pm$ 0.12 <sup>b</sup>	8.91 $\pm$ 0.12 <sup>c</sup>
Pozitsia Odeska, CA-64 0.04%	7.92 $\pm$ 0.11 <sup>d</sup>	8.23 $\pm$ 0.11 <sup>d</sup>	7.61 $\pm$ 0.10 <sup>d</sup>	7.92 $\pm$ 0.11 <sup>d</sup>
MIP Feeriya	8.00 $\pm$ 0.12 <sup>a</sup>	8.38 $\pm$ 0.12 <sup>a</sup>	8.12 $\pm$ 0.13 <sup>a</sup>	8.17 $\pm$ 0.14 <sup>a</sup>
MIP Feeriya, CA-64 0.01%	8.27 $\pm$ 0.11 <sup>b</sup>	8.77 $\pm$ 0.10 <sup>b</sup>	8.45 $\pm$ 0.10 <sup>b</sup>	8.50 $\pm$ 0.10 <sup>b</sup>
MIP Feeriya, CA-64 0.02%	8.61 $\pm$ 0.11 <sup>c</sup>	8.99 $\pm$ 0.10 <sup>c</sup>	8.75 $\pm$ 0.10 <sup>c</sup>	8.78 $\pm$ 0.10 <sup>c</sup>
MIP Feeriya, CA-64 0.04%	7.71 $\pm$ 0.10 <sup>d</sup>	8.03 $\pm$ 0.12 <sup>d</sup>	7.82 $\pm$ 0.11 <sup>d</sup>	7.85 $\pm$ 0.11 <sup>d</sup>
Tenor	7.67 $\pm$ 0.12 <sup>a</sup>	8.10 $\pm$ 0.11 <sup>c</sup>	7.57 $\pm$ 0.11 <sup>a</sup>	7.78 $\pm$ 0.14 <sup>a</sup>
Tenor, CA-64 0.01%	8.00 $\pm$ 0.11 <sup>b</sup>	8.41 $\pm$ 0.10 <sup>b</sup>	7.88 $\pm$ 0.10 <sup>b</sup>	8.10 $\pm$ 0.10 <sup>b</sup>
Tenor, CA-64 0.02%	8.31 $\pm$ 0.10 <sup>c</sup>	8.66 $\pm$ 0.10 <sup>c</sup>	8.11 $\pm$ 0.11 <sup>c</sup>	8.36 $\pm$ 0.10 <sup>c</sup>
Tenor, CA-64 0.04%	7.55 $\pm$ 0.09 <sup>a</sup>	7.85 $\pm$ 0.10 <sup>d</sup>	7.30 $\pm$ 0.11 <sup>d</sup>	7.57 $\pm$ 0.10 <sup>a</sup>
MV Nador	8.03 $\pm$ 0.10 <sup>a</sup>	8.45 $\pm$ 0.11 <sup>a</sup>	8.14 $\pm$ 0.10 <sup>a</sup>	8.21 $\pm$ 0.26 <sup>a</sup>
MV Nador, CA-64 0.01%	8.34 $\pm$ 0.10 <sup>b</sup>	8.97 $\pm$ 0.10 <sup>a</sup>	8.44 $\pm$ 0.11 <sup>a</sup>	8.58 $\pm$ 0.10 <sup>b</sup>
MV Nador, CA-64 0.02%	8.69 $\pm$ 0.10 <sup>c</sup>	9.23 $\pm$ 0.10 <sup>c</sup>	8.81 $\pm$ 0.10 <sup>c</sup>	8.91 $\pm$ 0.10 <sup>c</sup>
MV Nador, CA-64 0.04%	7.70 $\pm$ 0.10 <sup>d</sup>	8.11 $\pm$ 0.11 <sup>d</sup>	7.90 $\pm$ 0.10 <sup>d</sup>	7.90 $\pm$ 0.10 <sup>d</sup>
MV Menrot	7.79 $\pm$ 0.10 <sup>a</sup>	8.62 $\pm$ 0.10 <sup>a</sup>	7.59 $\pm$ 0.11 <sup>a</sup>	8.00 $\pm$ 0.23 <sup>a</sup>
MV Menrot, CA-64 0.01%	8.11 $\pm$ 0.10 <sup>b</sup>	8.91 $\pm$ 0.10 <sup>b</sup>	7.90 $\pm$ 0.11 <sup>b</sup>	8.31 $\pm$ 0.11 <sup>b</sup>
MV Menrot, CA-64 0.02%	8.53 $\pm$ 0.11 <sup>c</sup>	9.23 $\pm$ 0.10 <sup>c</sup>	8.29 $\pm$ 0.12 <sup>c</sup>	8.68 $\pm$ 0.11 <sup>c</sup>
MV Menrot, CA-64 0.04%	7.52 $\pm$ 0.10 <sup>d</sup>	8.12 $\pm$ 0.10 <sup>d</sup>	7.89 $\pm$ 0.11 <sup>d</sup>	7.84 $\pm$ 0.10 <sup>d</sup>

Notes: values within a row marked with different letters are significantly different ( $P < 0.05$ ), according to Tukey's HSD test adjusted by the Bonferroni correction. Each comparison was conducted independently for every variety across the CA-64 treatment concentrations.

**Table 3**  
Yield of winter wheat varieties under the action of CA-79 ( $\bar{x} \pm SD$ ,  $n = 9$ )

Variant	Yield, t/ha			
	2023	2024	2025	average
Pozitsia Odeska	8.24 $\pm$ 0.11 <sup>a</sup>	8.63 $\pm$ 0.12 <sup>a</sup>	7.90 $\pm$ 0.11 <sup>a</sup>	8.26 $\pm$ 0.14 <sup>a</sup>
Pozitsia Odeska, CA-79 0.01%	8.89 $\pm$ 0.11 <sup>b</sup>	9.11 $\pm$ 0.12 <sup>b</sup>	8.47 $\pm$ 0.11 <sup>b</sup>	8.82 $\pm$ 0.11 <sup>a</sup>
Pozitsia Odeska, CA-79 0.02%	9.23 $\pm$ 0.10 <sup>c</sup>	9.45 $\pm$ 0.12 <sup>c</sup>	8.81 $\pm$ 0.11 <sup>b</sup>	9.16 $\pm$ 0.11 <sup>b</sup>
Pozitsia Odeska, CA-79 0.04%	7.99 $\pm$ 0.11 <sup>a</sup>	8.12 $\pm$ 0.11 <sup>d</sup>	7.44 $\pm$ 0.10 <sup>d</sup>	7.85 $\pm$ 0.11 <sup>c</sup>
MIP Feeriya	8.00 $\pm$ 0.12 <sup>a</sup>	8.38 $\pm$ 0.12 <sup>a</sup>	8.12 $\pm$ 0.13 <sup>a</sup>	8.17 $\pm$ 0.14 <sup>a</sup>
MIP Feeriya, CA-79 0.01%	8.47 $\pm$ 0.11 <sup>b</sup>	8.89 $\pm$ 0.10 <sup>b</sup>	8.67 $\pm$ 0.10 <sup>b</sup>	8.68 $\pm$ 0.10 <sup>a</sup>
MIP Feeriya, CA-79 0.02%	8.89 $\pm$ 0.11 <sup>c</sup>	9.23 $\pm$ 0.10 <sup>c</sup>	8.98 $\pm$ 0.10 <sup>c</sup>	9.03 $\pm$ 0.10 <sup>b</sup>
MIP Feeriya, CA-79 0.04%	7.70 $\pm$ 0.10 <sup>d</sup>	8.01 $\pm$ 0.12 <sup>d</sup>	7.65 $\pm$ 0.11 <sup>d</sup>	7.79 $\pm$ 0.11 <sup>c</sup>
Tenor	7.67 $\pm$ 0.12 <sup>a</sup>	8.10 $\pm$ 0.11 <sup>c</sup>	7.57 $\pm$ 0.11 <sup>a</sup>	7.78 $\pm$ 0.14 <sup>a</sup>
Tenor, CA-79 0.01%	8.23 $\pm$ 0.11 <sup>b</sup>	8.64 $\pm$ 0.10 <sup>b</sup>	7.99 $\pm$ 0.10 <sup>b</sup>	8.29 $\pm$ 0.10 <sup>b</sup>
Tenor, CA-79 0.02%	8.57 $\pm$ 0.10 <sup>c</sup>	8.89 $\pm$ 0.10 <sup>c</sup>	8.41 $\pm$ 0.11 <sup>c</sup>	8.62 $\pm$ 0.10 <sup>c</sup>
Tenor, CA-79 0.04%	7.65 $\pm$ 0.09 <sup>a</sup>	7.80 $\pm$ 0.10 <sup>d</sup>	7.20 $\pm$ 0.10 <sup>d</sup>	7.55 $\pm$ 0.10 <sup>a</sup>
MV Nador	8.03 $\pm$ 0.10 <sup>a</sup>	8.45 $\pm$ 0.11 <sup>a</sup>	8.14 $\pm$ 0.10 <sup>a</sup>	8.21 $\pm$ 0.26 <sup>a</sup>
MV Nador, CA-79 0.01%	8.55 $\pm$ 0.10 <sup>b</sup>	9.12 $\pm$ 0.10 <sup>a</sup>	8.56 $\pm$ 0.11 <sup>a</sup>	8.74 $\pm$ 0.10 <sup>b</sup>
MV Nador, CA-79 0.02%	8.78 $\pm$ 0.10 <sup>c</sup>	9.50 $\pm$ 0.10 <sup>c</sup>	8.99 $\pm$ 0.10 <sup>c</sup>	9.09 $\pm$ 0.10 <sup>c</sup>
MV Nador, CA-79 0.04%	7.64 $\pm$ 0.10 <sup>d</sup>	8.01 $\pm$ 0.11 <sup>d</sup>	7.76 $\pm$ 0.10 <sup>d</sup>	7.80 $\pm$ 0.10 <sup>d</sup>
MV Menrot	7.79 $\pm$ 0.10 <sup>a</sup>	8.62 $\pm$ 0.10 <sup>a</sup>	7.59 $\pm$ 0.11 <sup>a</sup>	8.00 $\pm$ 0.23 <sup>a</sup>
MV Menrot, CA-79 0.01%	8.34 $\pm$ 0.10 <sup>b</sup>	8.99 $\pm$ 0.10 <sup>b</sup>	8.11 $\pm$ 0.11 <sup>b</sup>	8.48 $\pm$ 0.10 <sup>b</sup>
MV Menrot, CA-79 0.02%	8.77 $\pm$ 0.11 <sup>c</sup>	9.61 $\pm$ 0.10 <sup>c</sup>	8.50 $\pm$ 0.10 <sup>c</sup>	8.96 $\pm$ 0.10 <sup>c</sup>
MV Menrot, CA-79 0.04%	7.54 $\pm$ 0.10 <sup>d</sup>	8.02 $\pm$ 0.10 <sup>d</sup>	7.67 $\pm$ 0.11 <sup>d</sup>	7.74 $\pm$ 0.10 <sup>d</sup>

Notes: values within a row marked with different letters are significantly different ( $P < 0.05$ ), according to Tukey's HSD test adjusted by the Bonferroni correction; each comparison was conducted independently for every variety across the CA-79 treatment concentrations.

The key parameters for shaping the yield structure include the number and weight of grains from the main spike, the weight of the grains per plant, and the thousand-grains weight (TGW). These metrics determine the mechanisms of yield formation; therefore, prioritizing how new growth regulators influence individual components and the specific pathways by which they enhance yield are a central questions in research. As for parameters of yield structure under action of CA-64 (Table 4), the number of grains in the main spike is highly variable and, in this case, cannot be used to predict higher yield. Concentration 0.02% delivers the highest values in all three traits for every variety, 0.01% is an intermediate, significant uplift, 0.04% is de-

pressive (lowest means). Most of the yield boost at 0.01–0.02% is driven by heavier main spikes and more grain per plant, TGW also increases but more moderately. For parameters main spike grain weight: +0.3–0.7 g at 0.02% (+25–55%), for grain weight per plant +0.5–1.2 g at 0.02% (+20–55%), for TGW +2.8–5.2 g at 0.02% (+7–12%). At 0.04%, all three traits fall below control.

By variety Pozitsia Odeska showed strong, graded stimulation; 0.02% adds +44% (weight of grains per main spike and plant), +12% TGW. 0.04% brought a decline. MIP Feeriya has one of the largest relative responses, 0.02% raised grain per-plant by +40% and TGW by +12%. 0.04% suppressed all traits. Tenor showed marked im-

provement at 0.02% (weight of grains per plant +56%; TGW +10%). 0.04% was clearly detrimental. For MV Nador (western ecotype) consistent, moderate gains were manifested at 0.02% (per-plant +34%, TGW +7.5%). 0.04% brought a decline in all traits. MV Menrot (western ecotype) showed robust response at 0.02% (weight of grains per plant +38%, TGW +8.8%). 0.04% depressed all traits strongly.

The greatest increase in parameters was for grain weight per plant: Tenor (+56%), MIP Feeriya (+40%), Menrot (+38%), Nador (+34%), Pozitsia (+44%) and TGW (absolute gain): Pozitsia (+5.24 g), MIP Feeriya (+5.00 g), Tenor (+4.10 g), Menrot (+3.56 g), Nador (+3.10 g). These two parameters showed greater yield increase

than weight of grains per spike (variety-dependent, for western ecotype on the same level). The best working concentration was 0.02% CA-64 for all varieties, though 0.01% is a safer, still-effective fallback, : 0.04% should be avoided (uniform suppression). Gains at 0.02% come from both TGW and spike/plant grains weight components, which is useful for pushing yield potential. ANOVA-analysis confirmed a significant variability in all parameters with changing concentrations ( $F = 24.44$ ;  $F_{0.05} = 2.11$ ;  $P = 1.46 \times 10^{-5}$ ). Significant differences by varieties were also detected ( $F = 10.34$ ;  $F_{0.05} = 2.20$ ;  $P = 0.001$ ). A statistically significant genotype  $\times$  concentration interaction was developed too ( $F = 6.51$ ;  $F_{0.05} = 3.11$ ;  $P = 0.01$ ).

**Table 4**  
Parameters of yield structure under action of CA-64 ( $x \pm SD$ ,  $n = 30$ )

Variant	From main spike		Weight of grains per plant, g.	TGW, g
	number of grains, pcs.	weight of grains, g.		
Pozitsia Odeska	28.40 $\pm$ 3.22 <sup>a</sup>	1.20 $\pm$ 0.21 <sup>a</sup>	2.70 $\pm$ 0.30 <sup>a</sup>	42.30 $\pm$ 0.90 <sup>a</sup>
Pozitsia Odeska, CA-64 0.01%	30.40 $\pm$ 2.21 <sup>a</sup>	1.60 $\pm$ 0.15 <sup>b</sup>	3.40 $\pm$ 0.30 <sup>b</sup>	44.04 $\pm$ 0.97 <sup>b</sup>
Pozitsia Odeska, CA-64 0.02%	30.90 $\pm$ 2.10 <sup>a</sup>	1.80 $\pm$ 0.17 <sup>b</sup>	3.90 $\pm$ 0.24 <sup>c</sup>	47.54 $\pm$ 0.90 <sup>c</sup>
Pozitsia Odeska, CA-64 0.04%	28.77 $\pm$ 2.35 <sup>a</sup>	1.12 $\pm$ 0.10 <sup>a</sup>	2.44 $\pm$ 0.19 <sup>a</sup>	40.15 $\pm$ 0.81 <sup>d</sup>
MIP Feeriya	35.40 $\pm$ 2.40 <sup>a</sup>	1.30 $\pm$ 0.20 <sup>a</sup>	2.90 $\pm$ 0.20 <sup>a</sup>	41.90 $\pm$ 1.00 <sup>a</sup>
MIP Feeriya, CA-64 0.01%	33.10 $\pm$ 2.10 <sup>a</sup>	1.71 $\pm$ 0.12 <sup>b</sup>	3.45 $\pm$ 0.21 <sup>b</sup>	43.99 $\pm$ 1.01 <sup>b</sup>
MIP Feeriya, CA-64 0.02%	34.11 $\pm$ 2.11 <sup>a</sup>	2.01 $\pm$ 0.11 <sup>c</sup>	4.05 $\pm$ 0.18 <sup>c</sup>	46.90 $\pm$ 1.21 <sup>c</sup>
MIP Feeriya, CA-64 0.04%	33.10 $\pm$ 2.10 <sup>a</sup>	1.01 $\pm$ 0.10 <sup>d</sup>	2.45 $\pm$ 0.15 <sup>d</sup>	40.17 $\pm$ 0.53 <sup>d</sup>
Tenor	30.70 $\pm$ 2.90 <sup>a</sup>	1.30 $\pm$ 0.10 <sup>a</sup>	2.20 $\pm$ 0.20 <sup>a</sup>	39.90 $\pm$ 1.00 <sup>a</sup>
Tenor, CA-64 0.01%	32.10 $\pm$ 2.91 <sup>a</sup>	1.55 $\pm$ 0.11 <sup>b</sup>	2.97 $\pm$ 0.22 <sup>b</sup>	42.11 $\pm$ 1.01 <sup>b</sup>
Tenor, CA-64 0.02%	32.60 $\pm$ 2.91 <sup>a</sup>	1.92 $\pm$ 0.10 <sup>c</sup>	3.42 $\pm$ 0.22 <sup>c</sup>	44.00 $\pm$ 1.00 <sup>c</sup>
Tenor, CA-64 0.04%	30.11 $\pm$ 2.70 <sup>a</sup>	1.01 $\pm$ 0.10 <sup>d</sup>	1.81 $\pm$ 0.12 <sup>a</sup>	37.73 $\pm$ 1.02 <sup>d</sup>
MV Nador	36.10 $\pm$ 2.50 <sup>a</sup>	1.30 $\pm$ 0.20 <sup>a</sup>	2.90 $\pm$ 0.20 <sup>a</sup>	41.10 $\pm$ 0.90 <sup>a</sup>
MV Nador, CA-64 0.01%	37.45 $\pm$ 2.41 <sup>a</sup>	1.62 $\pm$ 0.13 <sup>b</sup>	3.42 $\pm$ 0.21 <sup>b</sup>	42.90 $\pm$ 0.67 <sup>b</sup>
MV Nador, CA-64 0.02%	36.22 $\pm$ 2.34 <sup>a</sup>	1.99 $\pm$ 0.14 <sup>c</sup>	3.89 $\pm$ 0.20 <sup>c</sup>	44.20 $\pm$ 0.56 <sup>c</sup>
MV Nador, CA-64 0.04%	34.55 $\pm$ 2.57 <sup>a</sup>	1.01 $\pm$ 0.13 <sup>d</sup>	2.42 $\pm$ 0.21 <sup>d</sup>	39.40 $\pm$ 0.90 <sup>d</sup>
MV Menrot	28.60 $\pm$ 3.70 <sup>a</sup>	1.40 $\pm$ 0.10 <sup>a</sup>	2.50 $\pm$ 0.20 <sup>a</sup>	40.60 $\pm$ 0.90 <sup>a</sup>
MV Menrot, CA-64 0.01%	29.10 $\pm$ 3.41 <sup>a</sup>	1.67 $\pm$ 0.14 <sup>b</sup>	3.10 $\pm$ 0.13 <sup>b</sup>	42.10 $\pm$ 0.56 <sup>b</sup>
MV Menrot, CA-64 0.02%	29.20 $\pm$ 3.13 <sup>a</sup>	1.98 $\pm$ 0.11 <sup>c</sup>	3.45 $\pm$ 0.11 <sup>c</sup>	44.16 $\pm$ 0.65 <sup>c</sup>
MV Menrot, CA-64 0.04%	29.76 $\pm$ 3.10 <sup>a</sup>	1.10 $\pm$ 0.10 <sup>d</sup>	2.00 $\pm$ 0.10 <sup>d</sup>	39.21 $\pm$ 0.40 <sup>d</sup>

Notes: values within a row marked with different letters are significantly different ( $P < 0.05$ ), according to Tukey's HSD test adjusted by the Bonferroni correction; each comparison was conducted independently for every variety across the CA-64 treatment concentrations.

As for parameters of yield structure under action of CA-79 (Table 5), the number of grains in the main spike was highly variable and, in this case, cannot be used to predict higher yield. Dose response is monotonic, 0.02% is the peak for all traits in every variety; 0.01% is a solid, significant uplift; 0.04% is uniformly depressive (lowest means).

Where the gains come from: The largest relative jumps are in sink size (main spike and per plant grain weight). TGW also rises but more moderately. Typical ranges (0.02% vs. water): grains weight per spike +0.6–0.9 g (+40–70%), grain weight per plant: +0.6–1.4 g

(+25–55%), TGW +3.3–6.6 g (+8–16%). By variety, Pozitsia Odeska showed strong, graded stimulation, 0.02% raised both grain weights and TGW, 0.04% was clearly harmful. MIP Feeriya was one of the largest responders, 0.02% raised plant grain weight by +46% and TGW by +5.6 g. 0.04% should be avoided. For Tenor, clear gains came at 0.02% (plant grain weight +60%, TGW +4.8 g), 0.04% depressed all traits. MV Nador (western ecotype) showed consistent, moderate response at 0.02% (TGW +3.3 g), 0.04% had a strongly negative effect. MV Menrot (western ecotype) showed robust uplift at 0.02% across all traits, 0.04% lowered them below control.

**Table 5**  
Parameters of action of CA-79 on yield structure ( $x \pm SD$ ,  $n = 30$ )

Variant	From main spike		Weight of grains per plant, g.	TGW, g
	number of grains, pcs.	weight of grains, g.		
Pozitsia Odeska	28.40 $\pm$ 3.22 <sup>a</sup>	1.20 $\pm$ 0.21 <sup>a</sup>	2.70 $\pm$ 0.30 <sup>a</sup>	42.30 $\pm$ 0.90 <sup>a</sup>
Pozitsia Odeska, CA-79 0.01%	30.80 $\pm$ 2.20 <sup>a</sup>	1.69 $\pm$ 0.11 <sup>b</sup>	3.49 $\pm$ 0.20 <sup>b</sup>	44.67 $\pm$ 0.77 <sup>b</sup>
Pozitsia Odeska, CA-79 0.02%	31.11 $\pm$ 2.11 <sup>a</sup>	1.91 $\pm$ 0.15 <sup>b</sup>	3.98 $\pm$ 0.20 <sup>c</sup>	47.89 $\pm$ 0.80 <sup>c</sup>
Pozitsia Odeska, CA-79 0.04%	28.11 $\pm$ 2.32 <sup>a</sup>	1.02 $\pm$ 0.10 <sup>a</sup>	2.24 $\pm$ 0.17 <sup>a</sup>	40.10 $\pm$ 0.71 <sup>d</sup>
MIP Feeriya	35.40 $\pm$ 2.40 <sup>a</sup>	1.30 $\pm$ 0.20 <sup>a</sup>	2.90 $\pm$ 0.20 <sup>a</sup>	41.90 $\pm$ 1.00 <sup>a</sup>
MIP Feeriya, CA-79 0.01%	33.17 $\pm$ 2.19 <sup>a</sup>	1.79 $\pm$ 0.11 <sup>b</sup>	3.66 $\pm$ 0.20 <sup>b</sup>	44.45 $\pm$ 0.91 <sup>b</sup>
MIP Feeriya, CA-79 0.02%	34.15 $\pm$ 2.15 <sup>a</sup>	2.21 $\pm$ 0.10 <sup>c</sup>	4.25 $\pm$ 0.15 <sup>c</sup>	47.50 $\pm$ 1.01 <sup>c</sup>
MIP Feeriya, CA-79 0.04%	33.44 $\pm$ 2.11 <sup>a</sup>	1.00 $\pm$ 0.11 <sup>d</sup>	2.33 $\pm$ 0.11 <sup>d</sup>	40.10 $\pm$ 0.43 <sup>d</sup>
Tenor	30.70 $\pm$ 2.90 <sup>a</sup>	1.30 $\pm$ 0.10 <sup>a</sup>	2.20 $\pm$ 0.20 <sup>a</sup>	39.90 $\pm$ 1.00 <sup>a</sup>
Tenor, CA-79 0.01%	32.56 $\pm$ 2.81 <sup>a</sup>	1.67 $\pm$ 0.10 <sup>b</sup>	3.07 $\pm$ 0.20 <sup>b</sup>	42.91 $\pm$ 0.71 <sup>b</sup>
Tenor, CA-79 0.02%	32.78 $\pm$ 2.71 <sup>a</sup>	1.99 $\pm$ 0.10 <sup>c</sup>	3.52 $\pm$ 0.20 <sup>c</sup>	44.67 $\pm$ 0.80 <sup>c</sup>
Tenor, CA-79 0.04%	30.00 $\pm$ 2.60 <sup>a</sup>	1.00 $\pm$ 0.11 <sup>d</sup>	1.71 $\pm$ 0.13 <sup>a</sup>	37.53 $\pm$ 0.52 <sup>d</sup>
MV Nador	36.10 $\pm$ 2.50 <sup>a</sup>	1.30 $\pm$ 0.20 <sup>a</sup>	2.90 $\pm$ 0.20 <sup>a</sup>	41.10 $\pm$ 0.90 <sup>a</sup>
MV Nador, CA-79 0.01%	37.11 $\pm$ 2.11 <sup>a</sup>	1.72 $\pm$ 0.13 <sup>b</sup>	3.42 $\pm$ 0.20 <sup>b</sup>	43.65 $\pm$ 0.45 <sup>b</sup>
MV Nador, CA-79 0.02%	37.22 $\pm$ 2.44 <sup>a</sup>	2.12 $\pm$ 0.12 <sup>c</sup>	3.91 $\pm$ 0.20 <sup>c</sup>	44.41 $\pm$ 0.46 <sup>c</sup>
MV Nador, CA-79 0.04%	35.55 $\pm$ 2.23 <sup>a</sup>	1.00 $\pm$ 0.13 <sup>d</sup>	2.31 $\pm$ 0.20 <sup>d</sup>	39.20 $\pm$ 0.70 <sup>d</sup>
MV Menrot	28.60 $\pm$ 3.70 <sup>a</sup>	1.40 $\pm$ 0.10 <sup>a</sup>	2.50 $\pm$ 0.20 <sup>a</sup>	40.60 $\pm$ 0.90 <sup>a</sup>
MV Menrot, CA-79 0.01%	29.34 $\pm$ 3.01 <sup>a</sup>	1.74 $\pm$ 0.14 <sup>b</sup>	3.30 $\pm$ 0.12 <sup>b</sup>	42.70 $\pm$ 0.46 <sup>b</sup>
MV Menrot, CA-79 0.02%	28.20 $\pm$ 3.00 <sup>a</sup>	2.18 $\pm$ 0.11 <sup>c</sup>	3.67 $\pm$ 0.11 <sup>c</sup>	44.86 $\pm$ 0.45 <sup>c</sup>
MV Menrot, CA-79 0.04%	28.76 $\pm$ 3.00 <sup>a</sup>	1.00 $\pm$ 0.10 <sup>d</sup>	2.02 $\pm$ 0.11 <sup>d</sup>	39.01 $\pm$ 0.33 <sup>d</sup>

Notes: values within a row marked with different letters are significantly different ( $P < 0.05$ ), according to Tukey's HSD test adjusted by the Bonferroni correction; each comparison was conducted independently for every variety across the CA-79 treatment concentrations.

Main spike grain is the most sensitive and shows the largest proportional gains at 0.02%. Grain weight per plant follows the same pattern, reinforcing that CA-79 expands sink capacity. TGW increases more modestly but consistently at 0.02% useful for maintaining grain size while boosting sink. Working dose for agronomic practice was 0.02%, CA-79 is the default choice for all tested varieties, 0.01% is a conservative, still-beneficial alternative. 0.04% should be avoided in every genotype as it brought uniform suppression of all three traits. Gains at 0.02% reflect a balanced improvement (larger spikes, plants plus heavier kernels), which should translate reliably to higher plot yield, as also seen in the multi-year yield tables.

ANOVA-analysis confirmed a significant variability in all parameters with changing concentrations ( $F = 28.39$ ;  $F_{0.05} = 2.11$ ;  $P = 8.17 \times 10^{-5}$ ). Significant differences by varieties were also detected ( $F = 10.45$ ;  $F_{0.05} = 2.20$ ;  $P = 0.001$ ). A statistically significant genotype  $\times$  concentration interaction was developed too ( $F = 7.78$ ;  $F_{0.05} = 3.11$ ;  $P = 0.008$ ).

CA-79 consistently outperforms CA-64 at the same concentration, especially at 0.02% and particularly for grain weight (main spike and per plant). TGW gains are also slightly larger with CA-79. The latter brought a stronger advantage, notably in TGW for MIP Feeriya and varieties of western ecotype (but they were less plastic than the local varieties). CA-79 again tended to outperform CA-64 on all traits for most varieties (e.g., Feeriya, Menrot, Tenor), indicating a broader stimulatory margin. At 4% both triazole compounds reduced all traits, with no material difference in “how bad,” though some varieties (e.g., Tenor, Menrot) showed very sharp drops under both agents. The practical message is the same, to avoid 0.04% for either compound. 0.02%, with CA-79 is preferred when the goal is maximum, balanced improvement. Local genotypes (Pozitsia, Feeriya, Tenor) exploit CA-79’s advantage best, western ecotypes (Nador, Menrot) still benefit, but the margin over CA-64 is moderate (largest for Menrot, smallest for Nador).

Grain quality was analyzed by the following traits: grain protein content, grain gluten content, the presence of high- and low-molecular-weight glutenins in the proteins and the total gliadin content. As shown in Table 6, CA-64 in 0.01–0.02% concentrations generally preserved protein and gluten while improving gluten composition (increase in HMW glutenins, often with lower content of LMW) and kept gliadins steady or slightly higher. 0.04% reliably reduced total protein or gluten in most varieties and damaged composition (de-

crease in HMW and LMW in several cases; gliadins tended to fall too). There was higher HMW with stable or lower LMW at 0.01–0.02%, this shift usually supports stronger dough and better bread volume.

For variety Pozitsia Odeska, protein and gluten were stable at 0.01–0.02%, protein fell at 0.04%; glutenins HMW rose at 0.01–0.02%, LMW was unchanged, gliadins were stable at 0.01–0.02%, down at 0.04%. 0.01–0.02% improved protein structure without protein/gluten penalty, and 0.04% should be avoided. MIP Feeriya for protein/gluten was largely stable, gluten rose at 0.01–0.02%; glutenins were unchanged, gliadins rose at 0.01–0.02%. 0.02% gave the best overall performance (higher glutenins, good gliadins). In Tenor protein peaked at 0.02%, fell at 0.04%; HMW glutenins were flat (0.15) until they fell at 0.04% (0.12), LMW rose at 0.04% (to 0.42); gliadins rose slightly at 0.02%, fell at 0.04%. 0.02% is the sweet spot (more protein, preserved structure), 0.04% was clearly adverse (HMW lower, LMW higher).

In MV Nador (western ecotype) protein/gluten were stable at 0.01–0.02%, both dropped at 0.04%. Glutenins HMW rose at 0.01–0.02%, LMW fell to 0.30 (positive), then rose to 0.36 at 0.04% (negative). Gliadins were stably high at 0.01–0.02%, down at 0.04%. Composition clearly improved at 0.01–0.02%, 0.04% harms both totals and fractions. MV Menrot (western ecotype) protein/gluten content rose at 0.02%, lowest at 0.04% (c). Glutenins content was a rise in HMW at 0.01–0.02%, a fall at 0.04%, LMW rose with concentration, peaked at 0.04%; gliadins rose at 0.01–0.02%, fell at 0.04% (c). The strongest improvement was at 0.02% (protein/gluten, HMW). 0.04% had worst effect (HMW and LMW).

For baking quality 0.02% is preferable (or 0.01% if risk-averse). Typically, there was a gain in HMW glutenins without inflating LMW and protein and gluten content were maintained; 0.04% should be avoided in all varieties, causing consistent losses in protein/gluten and unfavorable fraction shifts (fall in HMW, rise in LMW content). Western types (MV Nador, MV Menrot) still benefit at 0.01–0.02% (notably cleaner HMW content rise and LMW content decrease in Nador), but are more vulnerable at 0.04%. Locals (Pozitsia, Feeriya, Tenor) responded predictably; Tenor was best overall at 0.02% (protein bump plus stable fractions). CA-64 should be used at 0.02% (0.01% acceptable) to subtly upgrade gluten quality, especially by raising HMW glutenins, without sacrificing total protein/gluten. Steer clear of 0.04%.

**Table 6**

Grain quality under action of CA-64 ( $x \pm SD$ ,  $n = 3$ )

Variant	Protein, %	Gluten, %	Glutenins, g		Gliadins, g
			HMW	LMW	
Pozitsia Odeska	13.7 $\pm$ 0.2 <sup>a</sup>	26.1 $\pm$ 0.4 <sup>a</sup>	0.15 $\pm$ 0.01 <sup>a</sup>	0.42 $\pm$ 0.01 <sup>a</sup>	0.40 $\pm$ 0.01 <sup>a</sup>
Pozitsia Odeska, CA-64 0.01%	13.6 $\pm$ 0.2 <sup>a</sup>	26.5 $\pm$ 0.4 <sup>a</sup>	0.17 $\pm$ 0.01 <sup>b</sup>	0.43 $\pm$ 0.01 <sup>a</sup>	0.41 $\pm$ 0.01 <sup>a</sup>
Pozitsia Odeska, CA-64 0.02%	13.8 $\pm$ 0.2 <sup>a</sup>	26.5 $\pm$ 0.4 <sup>a</sup>	0.18 $\pm$ 0.02 <sup>b</sup>	0.42 $\pm$ 0.02 <sup>a</sup>	0.41 $\pm$ 0.02 <sup>a</sup>
Pozitsia Odeska, CA-64 0.04%	13.2 $\pm$ 0.2 <sup>b</sup>	26.0 $\pm$ 0.4 <sup>a</sup>	0.12 $\pm$ 0.01 <sup>c</sup>	0.42 $\pm$ 0.01 <sup>a</sup>	0.37 $\pm$ 0.02 <sup>b</sup>
MIP Feeriya	13.6 $\pm$ 0.1 <sup>a</sup>	27.0 $\pm$ 0.2 <sup>a</sup>	0.23 $\pm$ 0.02 <sup>a</sup>	0.41 $\pm$ 0.02 <sup>a</sup>	0.51 $\pm$ 0.02 <sup>a</sup>
MIP Feeriya, CA-64 0.01%	13.7 $\pm$ 0.1 <sup>a</sup>	27.5 $\pm$ 0.3 <sup>a</sup>	0.22 $\pm$ 0.02 <sup>a</sup>	0.44 $\pm$ 0.01 <sup>b</sup>	0.54 $\pm$ 0.01 <sup>b</sup>
MIP Feeriya, CA-64 0.02%	13.7 $\pm$ 0.2 <sup>a</sup>	27.6 $\pm$ 0.4 <sup>a</sup>	0.24 $\pm$ 0.02 <sup>a</sup>	0.43 $\pm$ 0.02 <sup>ab</sup>	0.54 $\pm$ 0.01 <sup>b</sup>
MIP Feeriya, CA-64 0.04%	13.1 $\pm$ 0.2 <sup>a</sup>	27.1 $\pm$ 0.2 <sup>a</sup>	0.18 $\pm$ 0.02 <sup>b</sup>	0.44 $\pm$ 0.01 <sup>b</sup>	0.48 $\pm$ 0.01 <sup>c</sup>
Tenor	13.8 $\pm$ 0.2 <sup>a</sup>	27.1 $\pm$ 0.2 <sup>a</sup>	0.15 $\pm$ 0.01 <sup>a</sup>	0.37 $\pm$ 0.02 <sup>a</sup>	0.41 $\pm$ 0.02 <sup>a</sup>
Tenor, CA-64 0.01%	13.8 $\pm$ 0.1 <sup>a</sup>	27.4 $\pm$ 0.2 <sup>a</sup>	0.15 $\pm$ 0.02 <sup>a</sup>	0.37 $\pm$ 0.01 <sup>a</sup>	0.42 $\pm$ 0.01 <sup>a</sup>
Tenor, CA-64 0.02%	14.3 $\pm$ 0.2 <sup>b</sup>	27.5 $\pm$ 0.3 <sup>a</sup>	0.15 $\pm$ 0.02 <sup>a</sup>	0.37 $\pm$ 0.01 <sup>a</sup>	0.43 $\pm$ 0.02 <sup>a</sup>
Tenor, CA-64 0.04%	13.2 $\pm$ 0.2 <sup>c</sup>	27.0 $\pm$ 0.4 <sup>a</sup>	0.12 $\pm$ 0.01 <sup>b</sup>	0.42 $\pm$ 0.02 <sup>b</sup>	0.37 $\pm$ 0.01 <sup>b</sup>
MV Nador	14.3 $\pm$ 0.2 <sup>a</sup>	28.7 $\pm$ 0.3 <sup>a</sup>	0.22 $\pm$ 0.01 <sup>a</sup>	0.32 $\pm$ 0.01 <sup>a</sup>	0.50 $\pm$ 0.01 <sup>a</sup>
MV Nador, CA-64 0.01%	14.2 $\pm$ 0.2 <sup>a</sup>	28.9 $\pm$ 0.2 <sup>a</sup>	0.25 $\pm$ 0.01 <sup>b</sup>	0.30 $\pm$ 0.01 <sup>a</sup>	0.51 $\pm$ 0.01 <sup>a</sup>
MV Nador, CA-64 0.02%	14.4 $\pm$ 0.2 <sup>a</sup>	28.9 $\pm$ 0.4 <sup>a</sup>	0.26 $\pm$ 0.02 <sup>b</sup>	0.30 $\pm$ 0.01 <sup>a</sup>	0.51 $\pm$ 0.01 <sup>a</sup>
MV Nador, CA-64 0.04%	13.7 $\pm$ 0.2 <sup>b</sup>	27.7 $\pm$ 0.2 <sup>b</sup>	0.19 $\pm$ 0.01 <sup>c</sup>	0.36 $\pm$ 0.01 <sup>b</sup>	0.45 $\pm$ 0.01 <sup>b</sup>
MV Menrot	14.0 $\pm$ 0.1 <sup>a</sup>	27.5 $\pm$ 0.2 <sup>a</sup>	0.15 $\pm$ 0.01 <sup>a</sup>	0.40 $\pm$ 0.01 <sup>a</sup>	0.41 $\pm$ 0.01 <sup>a</sup>
MV Menrot, CA-64 0.01%	14.0 $\pm$ 0.3 <sup>a</sup>	27.6 $\pm$ 0.2 <sup>a</sup>	0.19 $\pm$ 0.01 <sup>b</sup>	0.43 $\pm$ 0.01 <sup>b</sup>	0.44 $\pm$ 0.01 <sup>b</sup>
MV Menrot, CA-64 0.02%	14.5 $\pm$ 0.1 <sup>b</sup>	28.0 $\pm$ 0.2 <sup>b</sup>	0.18 $\pm$ 0.01 <sup>b</sup>	0.42 $\pm$ 0.02 <sup>ab</sup>	0.44 $\pm$ 0.01 <sup>b</sup>
MV Menrot, CA-64 0.04%	13.5 $\pm$ 0.2 <sup>c</sup>	26.7 $\pm$ 0.2 <sup>c</sup>	0.12 $\pm$ 0.02 <sup>c</sup>	0.46 $\pm$ 0.01 <sup>c</sup>	0.37 $\pm$ 0.01 <sup>c</sup>

Notes: values within a row marked with different letters are significantly different ( $P < 0.05$ ), according to Tukey’s HSD test adjusted by the Bonferroni correction; each comparison was conducted independently for every variety across the CA-64 treatment concentrations.

Thus, this trait showed a substantial difference between genotypes in the responsiveness to CA-64 and generally depended on the genotype of the original variety ( $F = 7.12$ ;  $F_{0.05} = 3.01$ ;  $P = 0.02$ ) and

concentrations of CA ( $F = 9.34$ ;  $F_{0.05} = 2.95$ ;  $P = 0.002$ ). A statistically significant genotype $\times$ CA-agent interaction was also developed ( $F = 5.07$ ;  $F_{0.05} = 5.04$ ;  $P = 0.05$ ).

As for CA-79 (Table 7), working range was 0.01–0.02% across all varieties, protein and gluten rose or stayed stable, with a consistent increase in HMW glutenins (quality-positive) and no LMW inflation (often unchanged). Gliadins were stable or slightly higher at these concentrations. Toxic zone was 0.04%. Nearly every variety showed lower protein and gluten, drop in HMW and lower gliadins, a clear decline in quality. Ranking by responsiveness, western ecotypes (MV Nador, MV Menrot) showed the largest protein/HMW gains at 0.01–0.02%; locals (Pozitsia Odeska, MIP Feeriya, Tenor) also improved,

with Tenor notably boosting protein at 0.02%. Variety Pozitsia Odeska at 0.01–0.02% showed improvement in both totals and structure (content of HMW). 0.04% is to be avoided. MIP Feeriya 0.02% is the clear sweet spot (more protein/gluten and HMW). Tenor under action of CA-79 showed a strong, clean uplift at 0.02%; 0.04% harmed all indices. MV Nador and MV Menrot (western ecotypes) showed a strong, quality-positive response at 0.02%; 0.04% reduced both totals and HMW.

**Table 7**

Grain quality under action of CA-79 ( $x \pm SD$ ,  $n = 3$ )

Variant	Protein, %	Gluten, %	Glutenins, g		Gliadins, g.
			HMW	LMW	
Pozitsia Odeska	13.7 ± 0.2 <sup>a</sup>	26.1 ± 0.4 <sup>a</sup>	0.15 ± 0.01 <sup>a</sup>	0.42 ± 0.01 <sup>a</sup>	0.40 ± 0.01 <sup>a</sup>
Pozitsia Odeska, CA-79 0.01%	13.9 ± 0.2 <sup>a</sup>	27.0 ± 0.4 <sup>b</sup>	0.18 ± 0.01 <sup>b</sup>	0.41 ± 0.01 <sup>a</sup>	0.42 ± 0.01 <sup>a</sup>
Pozitsia Odeska, CA-79 0.02%	14.2 ± 0.2 <sup>ab</sup>	27.5 ± 0.4 <sup>b</sup>	0.18 ± 0.02 <sup>b</sup>	0.41 ± 0.02 <sup>a</sup>	0.42 ± 0.02 <sup>a</sup>
Pozitsia Odeska, CA-79 0.04%	13.1 ± 0.2 <sup>c</sup>	25.5 ± 0.4 <sup>a</sup>	0.11 ± 0.01 <sup>c</sup>	0.43 ± 0.02 <sup>a</sup>	0.35 ± 0.02 <sup>b</sup>
MIP Feeriya	13.6 ± 0.1 <sup>a</sup>	27.0 ± 0.2 <sup>a</sup>	0.23 ± 0.02 <sup>a</sup>	0.41 ± 0.02 <sup>a</sup>	0.51 ± 0.02 <sup>a</sup>
MIP Feeriya, CA-79 0.01%	13.9 ± 0.1 <sup>b</sup>	27.7 ± 0.3 <sup>b</sup>	0.27 ± 0.01 <sup>b</sup>	0.43 ± 0.01 <sup>a</sup>	0.51 ± 0.01 <sup>a</sup>
MIP Feeriya, CA-79 0.02%	14.2 ± 0.2 <sup>b</sup>	27.9 ± 0.4 <sup>b</sup>	0.28 ± 0.01 <sup>b</sup>	0.43 ± 0.02 <sup>a</sup>	0.52 ± 0.01 <sup>a</sup>
MIP Feeriya, CA-79 0.04%	13.0 ± 0.2 <sup>c</sup>	26.2 ± 0.2 <sup>c</sup>	0.15 ± 0.02 <sup>c</sup>	0.43 ± 0.01 <sup>a</sup>	0.44 ± 0.01 <sup>b</sup>
Tenor	13.8 ± 0.2 <sup>a</sup>	27.1 ± 0.2 <sup>a</sup>	0.15 ± 0.01 <sup>a</sup>	0.37 ± 0.02 <sup>a</sup>	0.41 ± 0.02 <sup>a</sup>
Tenor, CA-79 0.01%	13.9 ± 0.1 <sup>a</sup>	27.9 ± 0.2 <sup>b</sup>	0.19 ± 0.01 <sup>b</sup>	0.38 ± 0.01 <sup>a</sup>	0.43 ± 0.01 <sup>a</sup>
Tenor, CA-79 0.02%	14.4 ± 0.2 <sup>b</sup>	27.8 ± 0.2 <sup>b</sup>	0.20 ± 0.01 <sup>b</sup>	0.38 ± 0.01 <sup>a</sup>	0.42 ± 0.02 <sup>a</sup>
Tenor, CA-79 0.04%	13.2 ± 0.2 <sup>c</sup>	26.4 ± 0.3 <sup>c</sup>	0.11 ± 0.01 <sup>c</sup>	0.37 ± 0.02 <sup>a</sup>	0.35 ± 0.01 <sup>b</sup>
MV Nador	14.3 ± 0.2 <sup>a</sup>	28.7 ± 0.3 <sup>a</sup>	0.22 ± 0.01 <sup>a</sup>	0.32 ± 0.01 <sup>a</sup>	0.50 ± 0.01 <sup>a</sup>
MV Nador, CA-79 0.01%	14.7 ± 0.1 <sup>b</sup>	28.9 ± 0.2 <sup>a</sup>	0.26 ± 0.01 <sup>b</sup>	0.31 ± 0.01 <sup>a</sup>	0.54 ± 0.01 <sup>b</sup>
MV Nador, CA-79 0.02%	14.8 ± 0.1 <sup>b</sup>	29.5 ± 0.4 <sup>b</sup>	0.27 ± 0.02 <sup>b</sup>	0.31 ± 0.01 <sup>a</sup>	0.55 ± 0.01 <sup>b</sup>
MV Nador, CA-79 0.04%	13.6 ± 0.2 <sup>c</sup>	27.4 ± 0.2 <sup>c</sup>	0.17 ± 0.01 <sup>c</sup>	0.32 ± 0.01 <sup>a</sup>	0.44 ± 0.01 <sup>c</sup>
MV Menrot	14.0 ± 0.1 <sup>a</sup>	27.5 ± 0.2 <sup>a</sup>	0.15 ± 0.01 <sup>a</sup>	0.40 ± 0.01 <sup>a</sup>	0.41 ± 0.01 <sup>a</sup>
MV Menrot, CA-79 0.01%	14.5 ± 0.1 <sup>b</sup>	27.5 ± 0.2 <sup>a</sup>	0.19 ± 0.01 <sup>b</sup>	0.41 ± 0.01 <sup>a</sup>	0.46 ± 0.01 <sup>b</sup>
MV Menrot, CA-79 0.02%	14.8 ± 0.1 <sup>c</sup>	28.5 ± 0.2 <sup>b</sup>	0.23 ± 0.01 <sup>c</sup>	0.42 ± 0.02 <sup>a</sup>	0.47 ± 0.02 <sup>b</sup>
MV Menrot, CA-79 0.04%	13.6 ± 0.2 <sup>d</sup>	26.5 ± 0.2 <sup>c</sup>	0.10 ± 0.02 <sup>d</sup>	0.42 ± 0.01 <sup>a</sup>	0.36 ± 0.01 <sup>c</sup>

Notes: values within a row marked with different letters are significantly different ( $P < 0.05$ ), according to Tukey's HSD test adjusted by the Bonferroni correction; each comparison was conducted independently for every variety across the CA-79 treatment concentrations.

CA-79 should be used at 0.02% as the primary quality-enhancing dose (0.01% is acceptable when a conservative approach is taken). One should expect a rise in protein, gluten, HMW glutenins without LMW inflation (i.e., a better gluten profile for breadmaking). One should avoid 0.04% in all genotypes: consistent drops in protein/gluten and HMW, plus gliadin loss. Western types profited most in absolute gains at 0.01–0.02%, but they were also the most penalized at 0.04%; locals responded predictably and safely at 0.02%.

Thus, this trait showed a substantial difference between genotypes in the responsiveness to CA-79 and generally depended on the genotype of the original variety ( $F = 7.45$ ;  $F_{0.05} = 3.01$ ;  $P = 0.02$ ) and concentrations of CA ( $F = 11.14$ ;  $F_{0.05} = 2.95$ ;  $P = 0.001$ ). A statistically significant genotype×CA-agent interaction was developed too ( $F = 5.45$ ;  $F_{0.05} = 5.04$ ;  $P = 0.04$ ).

In general for the grain quality stimulatory window (0.01–0.02%): both agents tend to improve quality, but CA-79 is consistently stronger and more uniform across traits and genotypes. The toxic zone (0.04%) depresses quality, yet the penalty is usually larger and more uniform with CA-79 (clear drops in protein, gluten, and HMW; gliadins also fall). CA-64 at 0.04% is also harmful, but some locals show slightly smaller absolute losses than under CA-79. For protein content action of CA-79, there were clear, significant rises at 0.01–0.02% at most cases (e.g., Pozitsia Odeska, Feeriya, Tenor, Nador, Menrot); CA-64 often had a stable to mild effect at 0.01–0.02%, still positive, but the gain is smaller/more genotype-dependent. At 0.04% both agents reduced protein, the drop was generally steeper with CA-79. For gluten, action of CA-79 brought +0.7% to +1.5% (typical) at 0.01–0.02% across both varieties, highly consistent. With CA-64 increases were present but more modest; still beneficial at 0.02%, especially in locals. At 0.04% CA-79 shows a clearer, across-the-board decrease. For glutenin profile HMW glutenins (desirable for dough strength) action of CA-79 brought robust increases at 0.01–0.02% in every variety. This is the clearest advantage of CA-79. CA-64 increases also occurred at 0.01–0.02%, but were smaller on average. At 0.04% HMW fell for both; the decrease being greater with

CA-79. LMW glutenins (often neutral or negative for baking) under action of both agents was largely stable through 0.01–0.02% (rare small shifts); there was no systematic inflation, which is good (quality rise comes mainly via HMW gains). At 0.04%, CA-64 sometimes showed an LMW uptick (e.g., Menrot), which can worsen quality, CA-79 kept LMW mostly flat, even at 0.04%. For gliadins 0.01–0.02% CA-79 often produced a modest increase (e.g., Feeriya, Nador, Menrot), while CA-64 was flat to slightly raised. For 0.04%, there was a decline in both CA-64 decline and CA-79, with CA-79 showing a cleaner, consistent drop across genotypes.

Local varieties (Pozitsia Odeska, MIP Feeriya, Tenor) subject to CA-79 0.02% showed the most reliable net improvement (protein, gluten, HMW increase, LMW steady). CA-64 (0.02%) was also positive, but gains (especially HMW magnitude) were typically smaller than CA-79. For western ecotypes (MV Nador, MV Menrot) CA-79 0.01% – 0.02% brought the largest absolute HMW and protein lifts among all varieties, standout response; CA-64 0.02% proved helpful but less potent than CA-79. Both compounds at 0.04% brought a sharp deterioration; western types were the most penalized.

The primary quality enhancer was CA-79 at 0.02% (or 0.01% if risk-averse). One should expect a consistent rise in protein, gluten and a tangible shift toward higher HMW glutenins without LMW inflation, ideal for breadmaking strength. A safe alternative or conservative choice is CA-64 at 0.02% (or 0.01%). Benefits are real but smaller; but still suitable when CA-79 access or regulatory status is limiting. One should avoid 0.04% for both agents in all varieties (quality indices drop, HMW particularly suffers).

For MV Nador and MV Menrot, one should prioritize CA-79 (0.01–0.02%), monitoring its use closely and never exceed 0.02%. For Pozitsia, Feeriya, Tenor, CA-79 (0.02%) delivers the most reliable uplift; CA-64 (0.02%) remains a dependable fallback. Both compounds can improve grain quality at low dose, but CA-79 has the stronger, more uniform effect, especially via HMW glutenin enrichment, making it the first choice at 0.02%. CA-64 is a solid, safer second line; 0.04% is universally counterproductive.

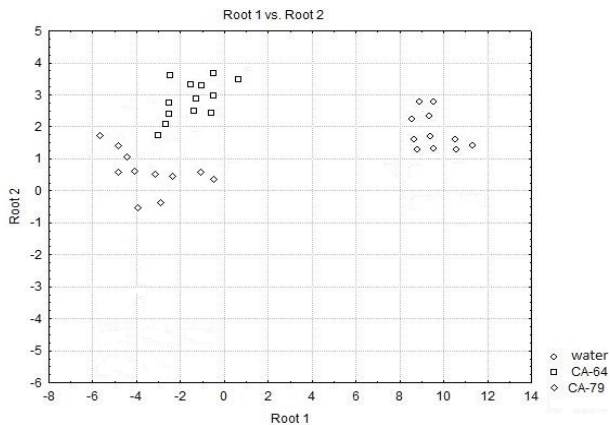
Factor analysis (Table 7) indicates that CA dose primarily drives variation in yield, grain weight per main spike, grain weight per plant, thousand-grain weight (TGW), protein and HMW glutenins capturing the major axes of phenotypic and quality change. Variety effects, by contrast, are strongest for yield, main-spike grain weight, TGW, protein, gluten, HMW glutenins and gliadins, summarizing how genotype shapes both productivity and quality traits. The variable set was sufficient for robust discrimination in both dose- and genotype-oriented models.

Despite relatively few traits being strictly genotype-dependent, the classification models retained high power to detect CA-driven responses in productivity and quality. Cross-validated assignment accuracy for yield traits was strong 76% for MIP Feeriya, 85% across the other locally adapted set and 88–91% for western-ecotype varieties.

**Table 8**  
Factor loadings (unrotated) and discriminant function

Parameter	Concentration	Geno-type	Wilks' - Lambda	F <sub>remove</sub> (5,01)	P-value
Yield	0.911*	0.857*	0.023	22.17	< 0.01
Weight of grains per main spike	0.710*	0.793*	0.016	17.45	< 0.01
Weight of grains per plant	0.897*	0.610	0.015	16.03	< 0.01
TGW	0.914*	0.880*	0.024	23.99	< 0.01
Protein	0.725*	0.749*	0.016	13.44	< 0.01
Gluten	0.645	0.711*	0.011	7.33	0.02
HMW	-0.723*	0.717*	0.015	15.14	< 0.01
LMW	-0.342	0.324	0.006	4.23	0.07
Gliadins	0.611	0.731*	0.021	13.22	< 0.01
Explanation variants	6.342	3.989	–	–	–
Non-explanation	0.553	0.434	–	–	–

Multivariate ordination further shows that MIP Feeriya and the western-ecotype varieties occupy a less favorable region of factor space than the other genotypes, yet all classes remain well captured by a well-fitting model. The factor-space map (Fig. 1) also separates the CA agents: CA-64 and CA-79 do not form a single cluster. Their effects on seed material differ significantly, although the spatial proximity of some objects suggests partially overlapping modes of action.



**Fig. 1.** Model for action on CA agents in factors space

A clear varietal bifurcation emerges: western-ecotype genotypes cluster together, while locally adapted lines form a second cluster, with MIP Feeriya showing minor boundary ambiguity. The dominant discriminant appears to be adaptation to the target environment, which drives the separation. Crucially, there is no substantial intermixing among genotypes in the analysis space; groups remain distinct and coherent, supporting reliable classification and interpretation.

## Discussion

Winter wheat is a cornerstone crop for global food security (Ukraine included) where yield hinges on the crop's capacity to cope with environmental stress and on the quality of agronomic management. In recent decades, attention has shifted toward next-generation growth stimulants that do more than nudge yield: they also temper

stress sensitivity and improve both technological and nutritional grain quality (Cohen et al., 2021; Nazarenko et al., 2023).

These stimulants span a heterogeneous set of synthetic and natural chemistries that act on metabolism, cell division, and tissue differentiation. Their impacts are typically expressed through activation of key enzymatic pathways, enhanced chlorophyll biosynthesis, and modulation of phytohormonal balance, auxins, cytokinins and gibberellins prominent among them, culminating in a measurable rise in photosynthetic efficiency (Feng et al., 2018; Xu et al., 2024). Modern formulations include triazole derivatives, amino acid complexes, humic substances, and epigenetically active agents, each offering partially overlapping yet distinct physiological levers. Functionally, these inputs accelerate and equalize germination, strengthen early root systems, expand leaf area, raise the fraction of productive tillers, fortify stems against lodging, and support more complete grain filling with a tendency toward higher protein accumulation. Under increasingly erratic climates, drought spells, abrupt temperature swings, uneven precipitation, such effects are especially valuable for stabilizing production (Rani et al., 2018; Obaid et al., 2025).

The most important agronomic dividend from stimulant use is yield stabilization and, in many cases, yield enhancement via optimization of core physiological processes. Seed or foliar applications frequently translate into faster stand establishment (higher germination energy, more uniform emergence), a larger and more efficient photosynthetic canopy, improved productive tillering, and a better balance between grains per spike and thousand-kernel weight (Rani et al., 2018; Kim et al., 2024). These gains accumulate across the season: stronger early vigor improves winter survival and spring regrowth, while sustained photosynthetic capacity during stem elongation and grain filling supports higher assimilate supply to the ear. Triazole-based regulators are particularly noteworthy for coupling morpho-physiological tuning (e.g., moderated plant height, sturdier culms, delayed senescence) with stress-mitigating effects, thereby aligning plant architecture and metabolism with the demands of intensive management. Equally relevant is quality. By elevating photosynthetic efficiency and smoothing the source sink relationship, stimulants can increase grain protein and adjust the composition of storage proteins in ways that favor bread-making quality (Nazarenko et al., 2022; Xu et al., 2022). When integrated into a broader technology package, timely sowing, balanced NPK and micronutrients, appropriate plant density, and fungicide programs, growth stimulants serve as a precision lever that enhances the return on routine inputs. Their value is maximized when dose and timing are tailored to genotype and environment: conservative rates for stress-sensitive materials or dry forecasts; more assertive programs for robust varieties under favorable moisture. In sum, modern stimulants, especially triazole-based formulations, provide a flexible, evidence-based path to stabilize and lift winter wheat yields while safeguarding grain quality amid the mounting pressures of climate variability (Mohsin et al., 2023; Mengistie & McDonald, 2023).

The experimental results in this case showed that these types of growth regulators positively affect photosynthetic activity regardless of genotype. It should be noted, however, that the trials were conducted in years that were generally favorable for wheat ontogenesis (Murphy et al., 2020; Ejaz et al., 2023). It was also reaffirmed that the potentially higher productivity of Western-ecotype cultivars is supported by elevated photosynthetic activity specifically during critical growth and development phases; another previously noted effect may be an extension of photosynthetic activity over time due to a longer ontogenetic period (Zhang et al., 2024; Liu et al., 2025). This aspect lay outside the scope of our study, although earlier work did establish later maturity dates for European cultivars compared with local ones (Iqbal et al., 2015; Ahmad et al., 2020).

At the same time, this trait can be either beneficial or moderately negative, because it indirectly drives higher water use precisely during the period most vulnerable to productive-moisture deficit. Drought at heading (May) can therefore cause much greater yield losses, in which case local germplasm would have the advantage. Such a feature should be considered when drawing up sowing plans with regard to

variety differentiation (Ali & Baloch, 2020). Under climate change, this tendency will only intensify.

With respect to yield, while confirming the positive effect of triazoles on this parameter (Jha et al., 2017; Liu et al., 2025), it should be emphasized that the studied cultivars follow two distinct pathways to higher productivity. As noted previously, in locally bred varieties the decisive factor is grain weight per plant (i.e., increased productive tillering, which also improves outcomes after winter), whereas in Western-ecotype varieties the advantage comes from forming a more productive main spike, so grain output from the main spike contributes more strongly. In both cases, however, thousand-grain weight (TGW), as an indicator of grain filling, plays a substantial and often greater role. Integratively, this can lead to an overall increase of up to 12% (Cohen et al., 2021; Ejaz et al., 2023).

Although the substances studied generally have a positive effect on overall grain quality at moderate concentrations, the mechanism involves not so much a direct rise in protein and gluten content as a shift in the proportions of components (glutenins) within the protein-gluten complex (Nazarenko et al., 2019; Kosová et al., 2021). The impact of triazoles is far more significant in improving baking quality by increasing the share of beneficial high-molecular-weight (HMW) components and reducing the contribution of unfavorable low-molecular-weight (LMW) components. Similar trends in crop protection agents were previously attributed to shifts in biotype composition in winter wheat cultivars (Peng et al., 2025). Gliadin variability is markedly lower (the lowest among the quality traits assessed) and contributes virtually nothing in this respect; protein variability is quite modest and yields meaningful gains primarily in cultivars that already have relatively high protein content. The same holds for total gluten content (Ahmad et al., 2020; Mohsin et al., 2021; Jiang, et al., 2023).

## Conclusion

Across varieties and measurement systems, triazole priming shows a narrow, repeatable stimulatory window at 0.01–0.02%, with a consistent toxicity threshold at 0.04%. Within the effective range, CA-79 outperforms CA-64 on photosynthetic status, yield, yield structure, and grain quality with CA-79 delivering the stronger and more consistent response across years and genotypes. CA-79 also tends to give larger gains in grain weight per main spike, grain weight per plant and TGW, particularly in MIP Feeriya and western ecotypes (MV Nador, MV Menrot), while still benefiting local types (Pozitsia Odeska, Tenor). Low-dose CA-79 (especially 0.02%) reliably increases protein and gluten and shifts the glutenin profile toward higher HMW fractions without inflating LMW, an advantageous pattern for baking strength. CA-64 at 0.02% is a safe, positive alternative, but gains are smaller. At 0.04%, both agents reduce quality indices; HMW glutenins drop most. Winter wheat quality improvement strongly depends on genotype. Locals (Pozitsia Odeska, MIP Feeriya, Tenor) have a predictable uplift at 0.02%; CA-79 is preferred, CA-64 is dependable as a fallback. Western ecotypes (MV Nador, MV Menrot) have clear benefits at 0.01–0.02%, with CA-79 giving the broader margin; one should not exceed 0.02%. CA-79 should be used at 0.02% as the default operational dose for maximal, balanced improvement in photosynthetic status, yield, and baking quality. When a risk-averse approach is taken or seed lots are sensitive, 0.01% offers a gentler, still significant uplift. CA-64 (0.02% or 0.01%) remains a good second choice when access or regulation limits use of CA-79. For both compounds 0.04% should be universally avoided. These studies will provide essential insights into how new triazole-based agents as growth regulators improve yield and quality traits of modern winter wheat varieties and show their stimulating effects on mechanisms of yield and grain quality formation. Investigation of micronutrient composition (Fe, Zn, Cu, Mn) will be planned.

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