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RESEARCH ARTICLE

Primary alarm signaling by ABA, SA, IAA, and gibberellins in winter rye (*Secale cereale*, *Poaceae*) during heat and chill exposure

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Abstract. The effects of short-term exposure to high (+40 °C, 2 h) and low positive temperature (+4 °C, 2 h) on hormonal homeostasis were analyzed in 14-day-old stressed and 21-day-old recovered plants of winter rye. A characteristic feature of the response to temperature stress was a rapid increase in abscisic acid (ABA) and salicylic acid (SA) levels—more pronounced after heat stress, particularly in the shoots. After both treatments, 14-day-old rye shoots showed an increase in gibberellins (GA_3+GA_4) and a decrease in indole-3-acetic acid (IAA) content. In the roots, chilling caused a slight reduction in SA, gibberellins, and IAA levels. In 21-day-old plants recovered after heat exposure, the levels of ABA and SA decreased in both organs, except for SA in the roots. Both ABA and SA accumulated mainly in the shoots, SA in the roots also increased and surpassed that in the shoots, IAA content remained lower than in the control. After chilling, the total gibberellin content in recovered plants decreased, whereas after heat stress it remained at control levels. In 21-day-old rye plants, GA_4 dominated after heat exposure, while GA_3 prevailed after chilling. These results reveal distinct organ-specific patterns in the reorganization of hormonal homeostasis during rapid adaptation to temperature stress.

Keywords: phytohormones, recovery, *Secale cereale*, temperature stresses

Introduction

Research on the impact of climate change on cereal productivity is one of the key priorities of modern biological science. Growing attention to this issue stems from the increasing intensity and frequency of climatic anomalies observed in recent years, including extreme temperature fluctuations, irregular precipitation, and other weather extremes (Ummenhofer, Meehl, 2017). Climate change triggers a range of biotic and abiotic stresses that influence the growth, development, and productivity of cereal crops (Raza et al., 2019; Kumar et al., 2025). Abnormally high or low temperatures adversely affect seed germination, seedling growth, photosynthesis, respiration, and nutrient uptake, accelerate senescence, and lead to yield reduction and grain quality deterioration (Liu et al., 2019; Hassan et al.,

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2021; Lal et al., 2022). Plants perceive environmental stressors and transmit these signals through cellular signaling pathways, inducing changes in gene expression and adjustments in metabolism and development (Zhang et al., 2020; Shrestha et al., 2022; Yu et al., 2025). To adapt to unfavorable conditions, plants have evolved specialized mechanisms for perceiving and processing stress signals, with phytohormones playing a central regulatory role (Verma et al., 2016). Phytohormones are signaling biomolecules of diverse chemical nature and physicochemical properties that function in nanomolar concentrations and regulate most physiological and metabolic processes throughout the plant life cycle—from seed germination to senescence. They are critical for integrating environmental signals into plant developmental programs, detecting stress factors, and incorporating these signals into endogenous regulatory networks that enable adaptation. The perception and transduction of stress signals leading to the activation of adaptive responses represent key steps in plant stress resistance (Panozzo et al., 2025). Therefore, determining the content and localization of phytohormones is crucial for understanding and potentially managing growth, development, and stress resistance (El Sabagh et al., 2022; Kosakivska et al., 2024).

At the early stages of plant response to temperature stress, growth inhibition is commonly associated with the suppression of gibberellin, auxin, and cytokinin biosynthesis—hormones that promote cell proliferation and elongation. This shift allows cereals to effectively redistribute energy and resources toward the synthesis of protective molecules, activation of antioxidant systems, and restructuring of cellular membranes (Rahman, 2013; Vanková et al., 2014; Wu et al., 2016). Specific hormonal alterations occur in different organs of cereal plants, forming a key component of their adaptive strategy to temperature stress (Jha et al., 2022; Raza et al., 2023). In some cases, strong correlations have been identified between hormone concentrations and the ability of plants to withstand unfavorable temperatures (Li et al., 2021; Raza et al., 2023). Changes in the content and distribution of abscisic acid can significantly affect the sensitivity of cereals to adverse environmental conditions by accelerating aging, reducing pollen fertility, and inducing seed dormancy (Gietler et al., 2020). Abscisic acid (ABA) enhances the resistance of wheat and maize to heat stress by regulating stomatal closure, stimulating root growth, and increasing the activity of antioxidant enzymes (Tao et al., 2022). In young rice panicles exposed to high temperatures, a decrease in the levels of active cytokinins, gibberellins, and indole-3-acetic acid (IAA), together with an increase in ABA and bound cytokinins, has been observed (Wu et al., 2016). The hormonal response of wheat varies depending on the duration and intensity of cold exposure. During the initial alarm phase (1 day), a rapid increase in ABA levels is accompanied by a decrease in active cytokinins and auxins and enhanced gibberellin deactivation. After 3–7 days of cold stress, ABA levels begin to decline, while levels of cytokinins, auxins, gibberellins, and salicylic acid (SA) increase. Prolonged exposure (21 days) leads to the establishment of a resistance phase (Kosová et al., 2012). Cluster analysis of wheat genotypes revealed that cold treatment induces the expression of genes involved in ABA and cytokinin metabolism, resulting in phytohormone accumulation (Kalapos et al., 2017). Hormonal interactions trigger corresponding physiological and morphological responses that enable plants to adapt to external stressors (Shi et al., 2015; Jha et al., 2022; Raza et al., 2023). The relationship between IAA and ABA has been explored in rice lines overexpressing the *OsGH3-2* gene, which encodes an enzyme responsible for conjugating IAA with amino acids. A reduction in free IAA content was accompanied by increased ABA levels and enhanced cold tolerance (Du et al., 2012). The formation of an auxin gradient through intracellular transport represents a key regulatory mechanism influencing plant growth, development, and yield under fluctuating temperatures (Rahman, 2013). Investigating the interactions among temperature stress responses, growth regulation, and hormonal signaling is therefore essential for understanding how cereals optimize development and yield under both high and low temperature conditions (Bidabadi, Abdel Latef, 2022).

Winter rye (*Secale cereale* L.) is an important cereal crop that ranks first among cereals cultivated in regions where wheat production is difficult or impossible (Bushuk, 2001). It is the most cold-tolerant of the cereal crops and less demanding of soil fertility and moisture than wheat. Unlike many other cereals, rye can be cultivated without herbicides and, in most cases, without fungicides, ensuring an environmentally friendly harvest (Arendt, Zannini, 2013). With the advancement of agriculture, the

advantages of rye—its winter hardiness, resilience, and low soil requirements—became increasingly evident (Behre, 1992).

Although the molecular mechanisms regulating temperature stress resistance in wheat, rice, barley, maize, and other cereals have been well studied, the physiological aspects of adaptive responses in rye remain comparatively underexplored. To comprehensively evaluate the physiological resilience of winter rye during early ontogenesis, a unified multi-target experimental model was established [14- and 21-day-old plants under heat stress (+40 °C, 2 h) and chilling (+4 °C, 2 h)]. Within this broader experimental framework, our previous research addressed cytokinin homeostasis and morphological growth recovery (Kosakivska et al., 2025), alongside cellular ultrastructural rearrangements (Babenko et al., 2024) and secondary metabolite dynamics under soil drought (Voytenko et al., 2025).

However, primary stress perception, stomatal dynamics, and early metabolic adjustments are governed by distinct signaling cascades operating upstream of or in coordination with cytokinin-mediated recovery mechanisms. While cytokinins predominantly control nutrient sink strength, cell division, and post-stress regeneration, the rapid alarm signaling phase is orchestrated by key stress-signaling phytohormones (ABA and SA) together with primary growth regulators (IAA and gibberellins). To prevent overcomplicating the narrative and to isolate the specific physiological functions of this early response, the present study focuses exclusively on this complementary phytohormonal panel. Therefore, the aim of the present study was to analyze the dynamics and organ-specific distribution of endogenous ABA, SA, IAA, and gibberellins (GA_3 and GA_4) in the shoots and roots of young winter rye plants during the initial alarm phase of heat stress and chilling, as well as during post-stress recovery. We hypothesized that short-term temperature stress induces rapid, highly coordinated adjustments in the ratio of stress-protective (ABA, SA) to growth-regulating (IAA, GAs) hormones, establishing a primary adaptive signaling pattern distinct from cytokinin-driven recovery mechanisms.

Materials and Methods

Plant material and experimental design. 'Boghuslavka' winter rye is a mid-season variety characterized by moderate drought, frost, and disease resistance, and is successfully cultivated on many Ukrainian farms. For the study of phytohormone accumulation and distribution, calibrated seeds were surface-sterilized in 70% ethanol for 1–2 min, rinsed thoroughly with distilled water, then placed on moistened filter paper in cuvettes and germinated in the dark at 21 °C for 24 h. Uniformly germinated seedlings were transplanted into 2 L pots filled with calcined river sand and grown in a Vötsch growth chamber (Balingen, Germany) under the following conditions: 20 °C day/17 °C night, 190 μmol $m^{-2} \cdot s^{-1}$ photon flux density, 16 h photoperiod, and 65 ± 5% relative humidity. Plants were watered daily with 50 mL Knop's solution per pot. The shoots and roots of 14- and 21-day-old plants were analyzed.

Temperature stress modeling and sampling. The experimental design and plant material were identical to those described in Kosakivska et al. (2025). To simulate heat stress, 14-day-old plants were exposed to +40 °C for two hours under illumination of 190 μmol $m^{-2} \cdot s^{-1}$. To simulate chill stress, 14-day-old plants were exposed to +4 °C for two hours under the same light conditions. For recovery, the plants were returned to controlled growth conditions and cultivated until day 21.

Extraction and analysis of phytohormones. Shoot and root samples (2 g each) were frozen in liquid nitrogen, ground to a homogeneous powder, and extracted with 10 mL of a methanol: distilled water: formic acid solution (15:4:1, v/v/v). Extraction was carried out for 24 hours at +4 °C in the dark. The extracts were centrifuged at 15,000 rpm for 30 minutes at 0 °C and evaporated under vacuum at +40 °C to a final aqueous volume of 5 mL. For further purification from lipophilic compounds, proteins, and pigments, a C18 Sep-Pak Plus cartridge (Waters, USA) was used. Phytohormones were sorbed using an Oasis MCX cartridge (6 cc/150 mg, Waters, USA). IAA, ABA, SA, and gibberellins (GA_3 and GA_4) were eluted with 100% methanol (acid fraction) according to the method described by Kosakivska et al. (2020). Phytohormones were quantified by high-performance liquid chromatography (HPLC) using an Agilent 1200 LC/MS system (USA) equipped with a G1315B diode array detector and an Agilent G6120A single quadrupole mass spectrometer. Chromatographic separation was performed on an Agilent ZORBAX Eclipse Plus C18 column (4.6 × 250 mm, 5 μm). For quantitative determination of SA, an Agilent

ZORBAX Eclipse Plus C18 SS column (3.0 × 150 mm, 3.5 μm) was used. Unlabeled standards of IAA, ABA, SA, GA_3, and GA_4 (Sigma-Aldrich, USA) were used to construct calibration curves. Detection was carried out in combined electrospray and chemical ionization modes at atmospheric pressure with negative ion polarity. Data acquisition and quantification were performed using Agilent OpenLAB CDS ChemStation Edition (rev. C.01.09).

Statistical analysis. Experiments were conducted in three biological replicates, each performed independently three times. Data were plotted using Microsoft Excel (Redmond, USA). Statistical analysis was carried out using SPSS 16.0 software (IBM SPSS Statistics, Chicago, USA). Treatment effects were analyzed using one-way ANOVA, with $P \leq 0.05$ considered statistically significant. Results in figures and tables are presented as mean ± standard error (SE).

Results

Abscisic acid accumulated more pronounced after heat stress than after chilling, particularly in the shoots. In recovered plants, the hormone content exceeded the control, and after chilling it was higher than in stressed plants. In the shoots of 14-day-old plants of 'Boghuslavka' winter rye, short-term exposure to high temperature (+40 °C, 2 hours) and chilling (+4 °C, 2 hours) caused an increase in ABA content by 137.0% and 61.6%, respectively. In the roots, heat stress led to a 150.5% increase in ABA, while chilling caused a 20.7% decrease (Fig. 1). After the cessation of high temperature, the ABA content in the shoots of 21-day-old recovered plants remained unchanged, whereas in the roots it decreased 1.4-fold. In the shoots, ABA level exceeded the control by 129%, while in the roots it remained within control values. After chilling, ABA continued to accumulate in 21-day-old recovered plants, more intensively in the roots (2.5-fold increase). As a result, the ABA levels in shoots and roots became nearly equal, exceeding the control by 79.7% and 8.6%, respectively (Fig. 1).

Salicylic acid accumulated in the shoots after heat stress. The hormone dominated in the roots of recovered after chilling plants. Following short-term heat stress and chilling, SA content in the shoots of 14-day-old plants of 'Boghuslavka' rye increased by 416.1% and 50.6%, respectively. In contrast, in the roots, SA levels decreased by 19.2% and 39.7% compared with the control (Fig. 2). During recovery after heat stress, the SA content in the shoots of 21-day-old plants slightly decreased (1.1-fold) but remained 101.2% higher than the control. After chill-stress recovery, SA levels in the shoots did not change and were 37.7% lower than the control. In the roots of recovered plants, SA content increased 1.3-fold after heat stress (still 11% lower than control) and 2.2-fold after chilling (16.4% higher than control) (Fig. 2).

The level of IAA decreased in roots more significantly after heat stress than after chilling. In the recovered plants, the hormone content continued to decrease. In the shoots of 14-day-old plants of 'Boghuslavka' rye, IAA content decreased under both heat stress and chilling, reaching 102.1 ± 5.1 and 107.6 ± 5.4 ng g^{-1} fresh weight (FW), respectively. A reduction in IAA was also observed in the roots – by 35.4% under heat stress and by 17.9% under chilling (Fig. 3). During the recovery period, IAA levels in the shoots and roots of 21-day-old plants decreased 3.2- and 1.7-fold after heat exposure, and 1.7- and 1.4-fold after chilling. The IAA content in the roots of plants recovered from both stresses was similar, at 48.4 ± 2.4 and 46.7 ± 2.3 ng g^{-1} FW, respectively (Fig. 3). The IAA levels in the shoots of recovered plants were 15.2% (after heat) and 51.7% (after chilling) lower than the control, while in the roots they were 32.1% and 29.1% lower, respectively.

The content of gibberellins in the shoots of stressed plants increased due to the accumulation of GA_4, while in the roots it decreased. In the shoots of 14-day-old plants of 'Boghuslavka' rye, the total content of gibberellins (GA_3+GA_4) increased by 6.1% and 20.7% under heat stress and chilling, respectively. These changes resulted from an increase in GA_4 levels, which reached 16.2 ± 0.8 and 15.9 ± 0.8 ng g^{-1} FW under stress conditions. In contrast, GA_3 content decreased markedly (2.5-fold) under heat stress. In the roots, total GA_3+GA_4 content decreased by 30.4% and 23.7% under high and low temperatures, respectively. Under heat stress, this reduction was due to a 2.2-fold decrease in GA_3, while chilling caused a 1.7-fold decrease in GA_4 (Fig. 4).

In the shoots of 21-day-old plants recovered after heat stress, GA_4 predominated, whereas after chilling, GA_3 was dominant. In the roots, the total GA_3+GA_4 content increased during recovery, more markedly after chilling, mainly due to GA_3 accumulation. After high-temperature stress cessation,

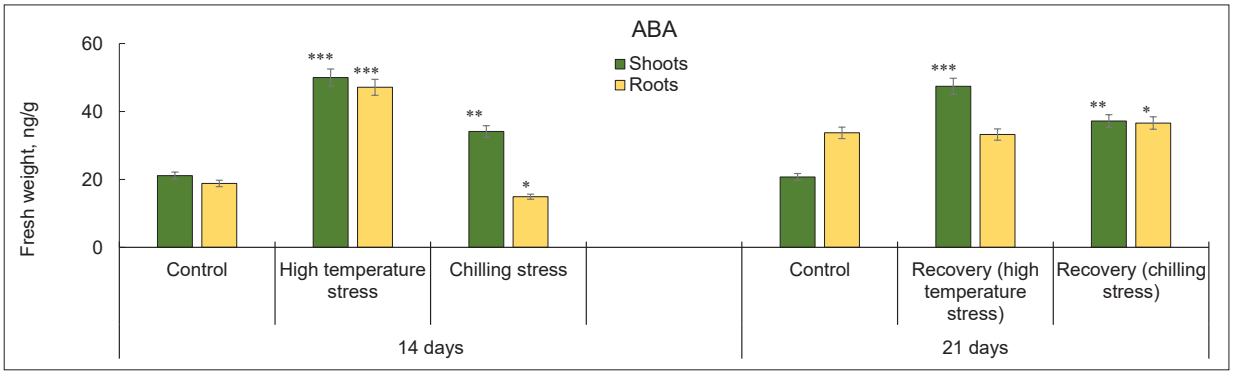


Fig. 1. Dynamics and distribution of endogenous abscisic acid in 14-day-old plants of *Secale cereale* 'Boghuslavka' after high temperature stress (+40 °C, 2 h), chilling (+4 °C, 2 h) and on the 21st day after recovery (ng/g FW). Significance at: * — $P < 0.05$, ** — $P < 0.01$ and *** — $P < 0.001$ compared with the control; n = 3; x ± standard error (SE)

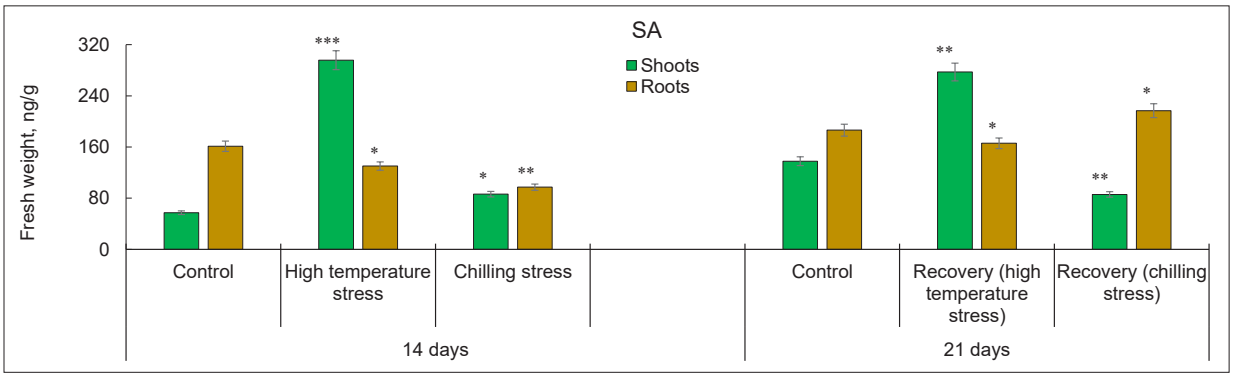


Fig. 2. Dynamics and distribution of endogenous salicylic acid in 14-day-old plants of *Secale cereale* 'Boghuslavka' after high temperature stress (+40 °C, 2 h), chilling (+4 °C, 2 h) and on the 21st day after recovery (ng/g FW). Significance at: * — $P < 0.05$, ** — $P < 0.01$, and *** — $P < 0.001$ compared with the control; n = 3; x ± standard error (SE)



Fig. 3. Dynamics and distribution of endogenous indole-3-acetic acid in 14-day-old plants of *Secale cereale* 'Boghuslavka' after high temperature stress (+40 °C, 2 h), chilling (+4 °C, 2 h) and on the 21st day after recovery (ng/g FW). Significance at: * — $P < 0.05$, ** — $P < 0.01$ and *** — $P < 0.001$ compared with the control; n = 3; x ± standard error (SE)

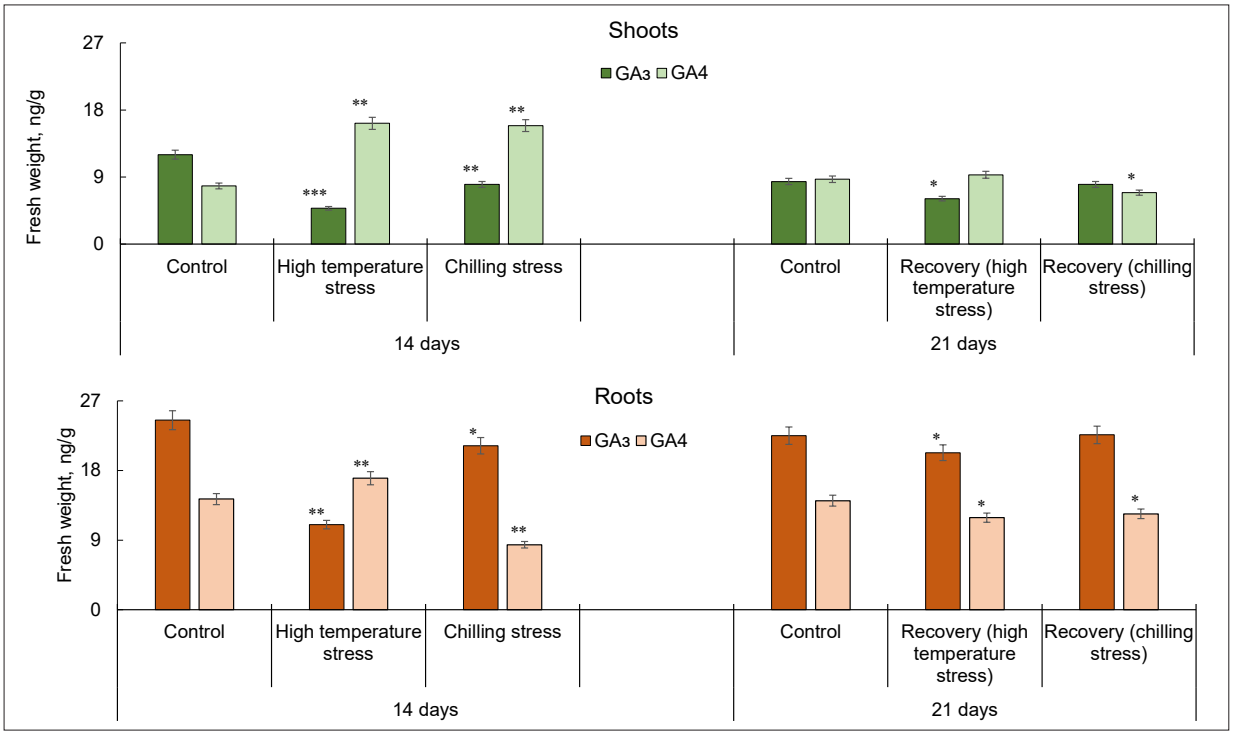


Fig. 4. Dynamics and distribution of endogenous gibberellins (GA_3 and GA_4) in 14-day-old plants of *Secale cereale* 'Boghuslavka' after high temperature stress (+40 °C, 2 h), chilling (+4 °C, 2 h) and on the 21st day after recovery (ng/g FW). Significance at: * — $P < 0.05$, ** — $P < 0.01$, and *** — $P < 0.001$ compared with the control; n = 3; x ± standard error (SE)

the balance between gibberellins in recovered plants shifted toward GA_3, whose content was 1.7 times higher than GA_4. In the roots, total GA_3+GA_4 content during recovery was 12% lower than the control after heat stress, but corresponded to control values after chilling (Fig. 4).

Discussion

The perception of environmental factors and the subsequent adaptive modification of plant growth occur through a complex, differentiated signaling system in which phytohormones play a key role. Changes in the accumulation and distribution of stress-dependent hormones are among the most dynamic physiological responses to stress, coordinating plant adaptation. Recent studies have demonstrated close interactions among phytohormones in shaping stress responses (Abhinandan et al., 2018; Khan et al., 2020). Nevertheless, each phytohormone occupies a distinct position in the cascade of external signal transduction and performs specific functions (Eyidogan et al., 2012). ABA is a key plant hormone that regulates responses to both high and low temperatures, enhancing stress tolerance through diverse physiological and biochemical mechanisms. Owing to its ability to move long distances, ABA serves as a central stress messenger. Its transport is a diffuse process involving specific ABA transporters (Boursiac et al., 2013). During stress, ABA is believed to connect roots and shoots, regulate water and ion transport, and, in coordination with other signaling molecules, mediate organ-to-organ communication (Xu et al., 2013; Vishwakarma et al., 2017). We observed that endogenous ABA accumulation in 'Boghuslavka' rye plants at the initial growth stage was more pronounced after heat stress, whereas chilling caused a reduction in ABA levels in roots (Fig. 1). The changes in ABA accumulation in recovered rye plants revealed the long-term, systemic effects of both heat and cold stress on ABA homeostasis. ABA-mediated responses to temperature stress influenced not only root growth but also cytokinin levels and other physiological parameters (Kosakivska et al., 2024b, 2025). Guo et al. (2023)

reported that ABA deficiency suppressed the response to low temperature (0 °C, 24 h) in barley plants at the early vegetative stage (three-leaf stage), disrupting chloroplast ultrastructure, altering starch and sucrose metabolism, reducing antioxidant enzyme activity, and modifying the hormonal network. In 14-day-old plants of a cold-resistant barley variety, exposure to low temperature (+5 °C, one day) significantly increased endogenous ABA content (Ahres et al., 2023). It has also been established that ABA enhances rice heat tolerance by regulating antioxidant enzyme activity, heat shock protein synthesis, and carbohydrate metabolism and transport to spikelets (Wu et al., 2016).

Salicylic acid (SA) enhances plant tolerance to both heat and cold stress by activating a series of protective mechanisms. Acting as a signaling molecule, SA triggers physiological and morphological responses that improve stress resistance (Yang et al., 2023; Kosakivska, Shcherbatiuk, 2025). Our findings revealed significant organ-specific differences in SA homeostasis under stress. In 14-day-old plants of 'Boghuslavka' rye, SA content in shoots increased after heat stress but decreased in roots following chilling. During recovery, SA levels in the shoots of plants exposed to high temperature exceeded the control, whereas root levels remained below control values. After chilling, the opposite trend was observed: SA levels were lower in shoots but higher in roots compared to controls (Fig. 2). Other studies have shown that under heat stress, SA reduces oxidative damage and mitigates the negative effects on plant growth and membrane stability, while under cold stress it enhances antioxidant enzyme activity, thereby minimizing damage and improving physiological performance (Liu et al., 2022). By strengthening antioxidant defenses, SA reduces the accumulation of reactive oxygen species (ROS) such as hydrogen peroxide (H_2O_2) and superoxide anions ($O_2\cdot^-$), which can damage plant cells at low temperatures (Zhang et al., 2021). SA also interacts with ABA to modulate stress responses (Zhang et al., 2022).

Auxin homeostasis under heat and cold stress depends on the plant species, developmental stage, and the intensity and duration of stress exposure (Jing et al., 2023; Gonzales, Kelley, 2025; Voytenko, Kosakivska, 2025). Our previous work on winter wheat and spelt demonstrated that IAA dynamics and localization during thermal stress were both organ- and species-specific: in wheat, roots were more stress-sensitive, whereas in spelt, shoots were more affected (Kosakivska et al., 2024a, 2024b). Similar patterns were observed in rye plants, where IAA content decreased under both heat and cold stress. The root system showed a stronger response to heat stress, and by the 21st day, a further decrease in hormone content indicated a prolonged stress effect (Fig. 3). It has been reported that reduced auxin levels under cold stress lead to root growth inhibition and morphological alterations (Tiwari et al., 2023).

In addition to regulating growth and development, gibberellins (GAs) actively participate in signaling pathways that mediate plant responses to abiotic stress. Under unfavorable environmental conditions such as drought, salinity, extreme temperatures, and nutrient deficiency, plants exhibit altered endogenous GA levels that influence stress tolerance (Kosakivska, Vasyuk, 2021). We found that in 14-day-old shoots of 'Boghuslavka' rye, the content of gibberellins GA_3+GA_4 increased under both high and low temperatures, while root levels decreased. During recovery after heat exposure, GAs content fell below control levels, whereas after chilling it returned to control values (Fig. 4). Under heat stress, GAs have been shown to increase the activity of antioxidant enzymes (SOD, CAT, POD) and the accumulation of osmolytes in wheat, thereby alleviating oxidative damage (Zhang et al., 2023; Romanenko et al., 2025). Gibberellins also positively influence root growth. A recent study indicated that histone deacetylases HDT1/2 mediate the early transition from cell division to elongation in root tips by suppressing transcription of the *GA2ox2* gene, which inactivates gibberellins (Li et al., 2017). The protective role of GAs in maintaining photosynthetic activity under heat stress has also been documented (Nagar et al., 2021). By regulating GAs levels, the negative impact of climate change on agricultural production can be reduced (Sakata et al., 2014).

Conclusions

Overall, our study revealed distinct effects of short-term high-temperature and chill stress on the dynamics and localization of four classes of endogenous phytohormones in 'Boghuslavka' winter rye during early vegetative growth and subsequent recovery. The results indicate that rye shoots and roots form distinct adaptive strategies in response to temperature stress. These findings provide the

foundations for further investigation of the hormonal mechanisms underlying cereal crop tolerance to high and low temperatures and for developing strategies for enhancing their adaptive potential.

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ETHICS DECLARATION

The authors declare no conflict of interest.

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Участь АБК, СК, ІОК та гіберелінів у формуванні первинної реакції-відповіді жита озимого (*Secale cereale*, *Poaceae*) за дії високої температури та охолодження

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Реферат. Досліджено вплив короткотривалої дії високої (+40 °С, 2 год) та низької позитивної температури (+4 °С, 2 год) на гормональний гомеостаз 14-добових стресованих та 21-добових відновлених рослин озимого жита. Характерною ознакою реакції на температурний стрес було швидке зростання вмісту абсцизової кислоти (АБК) та саліцилової кислоти (СК), більш інтенсивне після теплового стресу, особливо у пагонах. Після обох стресів зафіксоване збільшення вмісту гіберелінів ($ГК_3$+$ГК_4$) та зменшення вмісту індоліл-3-оцтової кислоти (ІОК). У коренях охолодження спричинило незначне зниження рівня СК, гіберелінів та ІОК. У 21-добових рослин, відновлених після теплового стресу, рівні АБК та СК знизилися в обох органах, за винятком СК у коренях. Як АБК, так і СК накопичувалися переважно у пагонах, вміст СК у коренях також збільшився та перевищив цей показник у пагонах, вміст ІОК залишався нижчим, ніж у контролі. Після охолодження загальний вміст гіберелінів у відновлених рослинах зменшився, тоді як після теплового стресу він залишався на рівні контролю. У 21-добових рослин жита після теплового стресу домінувала $ГК_4$, тоді як після охолодження переважала $ГК_3$. Отримані результати демонструють органоспецифічні закономірності реорганізації гормонального гомеостазу під час швидкої адаптації до температурного стресу.

Ключові слова: відновлення, температурні стреси, фітогормони, *Secale cereale*