

CORN RESILIENCE: INFLUENCE OF TEMPERATURE CHANGES AND BIOREGULATORS ON GERMINATION CHARACTERISTICS AND YIELD

Elena LUTCAN¹, Ala BOROVSKAIA¹, Dina ELISOVETCAIA¹,
Nicolai VANICOVICI², Raisa IVANOVA¹

¹Moldova State University, Institute of Genetics, Physiology and Plant Protection,
20 Padurii Street, Chisinau, MD-2002, Republic of Moldova

²National Centre of Research and Seed Production, "Porumbeni" sector,
S. Pascani, Republic of Moldova

Corresponding author email: elena.lutcan@sti.usm.md

Abstract

Based on research data and practical observations, the effect of temperature changes on the characteristics of corn germination was analyzed and the role of JS bioregulator, isolated from Juniperus sabina L. plants and used in increasing corn resistance to abiotic stress was assessed. The studies were conducted on corn hybrids Porumbeni 465 (P465) and Porumbeni 398 (P398) with dent (P465) and flint (P398) grain endosperm in laboratory and field conditions. The modification of root/ seedling length and vigor, as well as metabolic efficiency of corn germination under influence of low (10°C) and high (50°C) temperatures and impact of natural growth regulator JS were also established. Comparison of germination characteristics in laboratory studies with corn emergence in the field and its yield made it possible to establish their correlation relationships, some of which were quite strong (≥ 0.65). In conclusion, it should be noted that the differences between the studied hybrids in physical structure, chemical composition of grain and maturity time are reflected in their resilience to temperature stress and response to treatment with a bioregulator.

Key words: corn seed, non optimal temperatures, bioregulator, growth characteristics, correlation.

INTRODUCTION

The negative impacts of climate change, caused by increasing average annual temperatures, changing precipitation patterns (more frequent droughts and floods), increasing atmospheric CO₂ concentrations and more frequent extreme weather events, significantly affect the growth, development, yield and quality of agricultural crops (Xue et al., 2021; Kanjevas et al., 2022; Del Buono et al., 2023; Hultgren et al., 2025).

Corn (*Zea mays* L.), one of the world's major food and forage crops, is particularly susceptible to extreme temperatures. Its productivity is critically dependent on climatic conditions, and the optimal range of daily temperatures for growth is approximately 22-25°C. Both high and low temperatures have a significant negative impact on the growth, development and yield of this crop. According to official data of National Bureau of Statistics, in 2024, the Republic of Moldova suffered a decrease in both the area under corn cultivation and the yield compared to previous years,

which is directly related to unfavorable weather conditions, in particular soil and atmospheric drought and excessively high temperatures from May to July. According to the National Bureau of Statistics, the area under corn cultivation for 2024 amounted to 414.7 thousand hectares, which is 17% lower than in 2021. The average corn yield in 2024 was 1.5-3 tons/ha, which was 40% lower than in 2021. In the southern regions of the country, crop losses reached 70-90%. Corn production in 2024 is estimated at 717 thousand tons, which is significantly below the five-year average. For comparison, in relatively favorable years (for example, 2021), the total corn harvest exceeded these data by 1.5 times. This fact clearly demonstrates the high vulnerability of Moldovan agriculture to climate change, which requires the implementation of adaptation strategies, such as the use of drought-tolerant and temperature stress resistant hybrids.

Although average annual temperatures are rising, weather instability leads to more frequent and abrupt temperature fluctuations, as

well as late spring cold snaps and even frosts, increasing the risk of damage to corn crops during the early stages of development. Therefore, studying the mechanisms of cold tolerance and developing methods to enhance the adaptive potential of agricultural crops remain priorities in modern plant physiology and breeding.

Maximum crop productivity under abiotic stress conditions can be maximal achieved through the exogenous application of biologically active substances, including growth regulators. The use of plant-based bioregulators represents a promising and environmentally friendly approach to enhancing plant adaptive potential and minimizing corn yield losses under climate change. Bioregulators not only improve plant metabolic activity but also actively participate in the fine regulation of all vital processes, including complex responses to abiotic stress, providing effective protection against negative environmental factors (García-García et al., 2020; Del Buono et al., 2023). Research and practical experience demonstrate that the use of bioregulators, particularly pre-sowing seed treatment, has a multifactorial positive effect on plant stability and development. Thus, seed treatment before exposure to low or high temperatures helps improve the mobilization and efficient use of seed reserve substances, ensuring a strong start to seedling growth even after heat stress (Borovskaia et al., 2023; Lutcan et al., 2024; Ivanova et al., 2024). Bioregulators stimulate the activity of key antioxidant enzymes (such as superoxide dismutase, catalase, and peroxidase), which effectively neutralize excess reactive oxygen species (ROS) that form in excess under stressful conditions and damage cellular structures (Zulfiqar & Ashraf, 2021; Khan et al., 2022; Navruzov et al., 2025; Rao et al., 2025). Plant growth bioregulators have some common features: they are synthesized by plants, cause metabolic changes, their effects are present even at very low concentrations, and some of them has also positive effect (antioxidant, antibacterial, anticancer) on mammals (Garban & Ilia, 2024).

The comprehensive analysis of the effects of hypo- and hyperthermia and role of natural bioregulator on key physiological growth

characteristics and final productivity of corn (*Zea mays* L.) was conducted in this study. The relevance of the study lies in the fact that the correlation between the morpho-biological characteristics of seed germination under normal conditions and non-optimal temperatures serves as a reliable criterion for selecting stress-resistant and high-yielding genotypes.

MATERIALS AND METHODS

The laboratory studies were carried out in 2025 year in the Institute of Genetics, Physiology and Plant Protection (IGPPP), Moldova State University (MSU), Republic of Moldova.

Corn seeds. The National Center of Research and Seed Production (“Porumbeni” sector) generously contributed the seeds of corn hybrids:

- Porumbeni 398 (P398), a mid-early maturing flint corn hybrid, belongs to the popcorn group, FAO 400. The kernel has a flinty consistency, characterized by a high specific gravity of vitreous endosperm. The kernel density is high and difficult to grind. The starchy kernels are tightly packed and firmly connected. The floury portion of the endosperm is present only near the embryo. The endosperm has a high protein content (16%), containing a starch by mixture of amylose (20-30%) and amylopectin (70-80%).

- Porumbeni 465 (P465), a late-ripening dent corn hybrid, FAO 460. The grain is dented with a floury endosperm. The grain density is low and easily crushed. The starch grains are loosely arranged, weakly bound by a protein matrix. They are composed primarily of amylopectin (over 90-95%). The grain is easily processed into fine flour and is used in the food and starch-molasses industries.

Natural bioregulator. The concentrated extract from aboveground parts of *Juniperus sabina* (bioregulator JS), was obtained and tested in laboratory as plant growth regulator (Elisovetcaia et al., 2024; Lutcan et al., 2024). Bioregulator JS diluted to a concentration of 0.01% was used to pre-germination or pre-sowing treatment of corn seeds.

The corn seeds were exposed to non-optimal temperatures by two tests.

Cold test. The seeds were germinated for 7 days at +10°C, after which they were transferred to optimal conditions of germination for 4 days (Milivojević et al., 2021).

Heat test. The seeds were kept in a water bath at +50°C for 30 minutes. Then they were germinated under optimal conditions for 7 days.

Germination under optimal conditions of untreated seeds (control) and seeds after cold or heat test was carried out in accordance with the provisions of international rules (ISTA, 2017). After germination, the overall seed germination, root and seedling length, root and seedling biomass, root and seedling vigor were assessed (Kerecki et al., 2021; Milivojević et al., 2021; Khan et al., 2022). The biomass of reserve substances that was spent for energetic support of physiological processes and respiration during seed germination as well as metabolic efficiency were calculated (Sikder et al., 2009; Borovskaia et al., 2023).

Field experiments were conducted during the 2025 growing season at the National Center of Research and Seed Production, “Porumbeni” sector. Control seeds and seeds treated with JS bioregulator were sown in the first 10 days of May, in a randomized manner in four replicates, two rows and 50 seeds on replicate. The characteristics of field emergence and corn yield were determined.

Statistical analysis. The obtained experimental data were processed by the statistical methods using the software package Statgraphics Plus 5.0. The ANOVA test was applied for variance analysis of characteristics, Student test in assessment of statistically significant differences between plots, and correlation was determined by Pearson coefficients.

Abbreviations used in figure.

Control – untreated seeds; **Control_JS** – seeds treated with solution of JS bioregulator; **Cold** – seeds exposed to cold test; **Cold_JS** – seeds pre-treated with JS bioregulator and exposed to cold test; **Thermo** - seeds exposed to heat test; **Thermo_JS** - seeds pre-treated with JS bioregulator and exposed to heat test.

RESULTS AND DISCUSSIONS

The overall germination of control seeds of the studied hybrids varied. The hybrid P398 had a lower initial germination rate (87.9%), with 48.7% of the mobilized reserve substances used

for root and seedling growth and 51.3% for energy and respiration maintenance during germination. This means that the seeds of this hybrid expended more reserve resources simply to maintain their vital functions. Metabolic efficiency, a measure of how effective corn seeds utilize reserve substances to support their vital functions, was 0.9493 (Figure 1).

The control seeds of the P465 hybrid demonstrated high overall germination (98.0%) under normal conditions. Its physiological processes were more coordinated and required less energy to support germination. During germination, this hybrid demonstrated a more favorable ratio of reserve substances spent on growth and energy maintenance. Most of the mobilized reserve substances were used directly for growth of roots and seedlings (50.8%), while a smaller portion was spent on energy and respiration (49.2%). This ensured rapid and vigorous germination and, consequently, higher metabolic efficiency of control seeds, which amounted to 0.9705 (Figure 1).

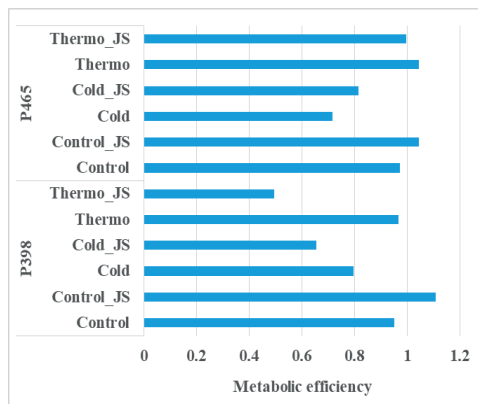


Figure 1. Metabolic efficiency of corn hybrids germinated under different conditions

Metabolic efficiency reflects how optimally and economically the seed embryo utilizes its internal nutrient reserves for two key processes: the construction of new structures - the biomass accumulation of seedlings and roots; and respiration, energy (ATP) production to support all life processes (El-Maarouf-Bouteau, 2022; Kanjevas et al., 2022). A comprehensive analysis of metabolic efficiency during germination confirms that the P465 dent corn hybrid is a slightly more economical and

physiologically vigorous hybrid. It converts internal resources into usable biomass more quickly and efficiently. Thus, the difference in metabolic efficiency between the two hybrids studied is due to their different physiological capabilities and genetically determined vigor, which directly influence how effectively they can mobilize and utilize their reserves for successful germination.

The study of corn resistance to non-optimal temperatures by cold- and heat tests also revealed significant hybrid differences.

The low temperatures cause profound metabolic depression to the P398 hybrid, despite maintaining high germination rate, which was comparable to control seeds. An increase in the consumption of reserve substances for respiration (4.45% higher than in seeds germinating under optimal conditions) indicates a redistribution of energy resources: a significant portion of endosperm reserves is expended on maintaining homeostasis (basic vital functions) rather than on structural processes (root and seedling growth). This leads to a 16.37% decrease in their metabolic efficiency (Figure 1).

Temperature stress acts as a limiting factor for the enzymatic activity responsible for the mobilization of reserve substances. Severe energy deficiency leads to a significant ($p \leq 0.001$) slowdown in morphogenesis: a reduction in the length of roots and seedlings by an average of 2.12-2.59 cm (Figure 2), and a decrease in root and seedling vigor by 43.48% and 53.40%, respectively (Figure 3). The flinty endosperm of the P398 hybrid is characterized by slow mobilization of reserve substances, especially at low temperatures due to the dense matrix. A diminution in root and seedling vigor while maintaining germination rate that the P398 hybrid enters a "passive survival" strategy (Kotak, 2007; Wang, et al, 2019; Sun at al., 2025). The resulting complex energy deficiency and metabolic disturbances pose risks for subsequent development in the field, requiring the use of bioregulators to optimize the use of reserve substances in seeds.

The high sensitivity of the P398 hybrid to temperature of 50°C was also established. This temperature is lethal or critically damaging for a significant amount (30%) of seeds, which is the primary indicator of severe heat stress and a

reduction in yield potential. Furthermore, it was showed the 60.88-63.78% reduction in vigor for roots and seedlings, compared to the same values obtained under optimal germination conditions (Figure 3). This is the most important characteristic, indicating a critical weakening of the surviving seedlings. Although the lengths of roots and seedlings increase by 18.02% and 15.32%, respectively, relative to the control (Figure 2). The observed increase in the linear size of organs is likely due to a disruption of homeostasis under stress.

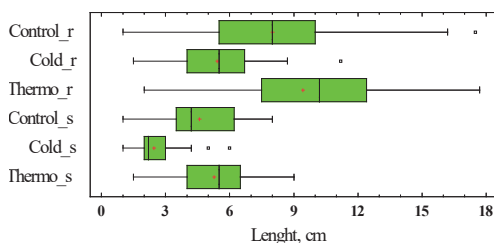


Figure 2. Root (r) and seedlings (s) length of P398 corn hybrid germinated under different conditions

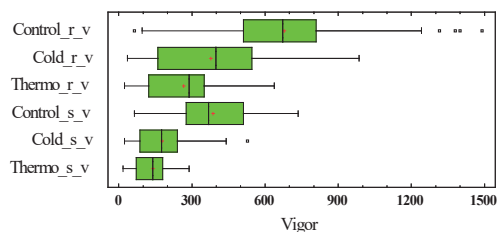


Figure 3. Root and seedlings vigor of P398 corn hybrid germinated under different conditions

Under abiotic stress, plants can rapidly elongate their organs, inefficiently utilize internal resources and form weak, nonviable structures (Rankenberg et al., 2021). Thus, the flint hybrid P398 exhibits low tolerance to heat stress (50°C), although surviving seeds exhibit some metabolic adaptation, with the change in their metabolic efficiency being insignificant ($p \leq 0.05$). However, the reduction in overall germination and the critical drop in vigor make this hybrid extremely vulnerable to the effects of such temperature at the germination stage, and its ability to withstand further stress and develop normally in field conditions is sharply reduced.

The pre-germination treatment of corn seeds with the JS bioregulator led to powerful stimulation of the initial growth and

development of roots and seedlings, as well as proved particularly effective for the genetically weaker hybrid P398. Metabolic efficiency increased by 17.04% compared to the seeds untreated with JS bioregulator, which reflecting more efficient mobilization of reserve substances such as starch, proteins, and fats for growth of roots and seedlings (Figure 1). The length of roots and seedlings of the P398 hybrid seeds, as well as their vigor was 18 - 19% higher than the control, indicating accelerated cell division and growth of the plant's organs. A well-developed root system and longer seedlings are critical for rapid plant establishment in the soil and access to moisture and nutrients during the early stages of vegetation. Vigor combines the speed of seedling emergence, their uniformity and ability to withstand stress. Seeds with high vigor produce stronger, more resilient plants. The use of the JS bioregulator in combination with temperature stress resulted in a significant ($p \leq 0.001$) suppression of root and seedling growth in the P398 hybrid in the cold test and an insignificant ($p \leq 0.05$) increase in root and seedling length in the heat test (Figure 4). However, root and seedling vigor decreased by 2.2-4.2 times in both the cold and heat tests (Figure 5), which was highly significant ($p \leq 0.001$).

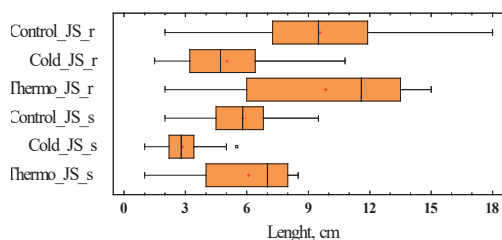


Figure 4. Root (r) and seedlings (s) length of P398 corn hybrid pre-treated with bioregulator JS and germinated under different conditions

The bioregulator is a powerful tool for managing the ontogenesis of intact seeds. However, using the JS bioregulator to treat seeds of a genetically unstable P398 hybrid exposed to non-optimal temperatures introduces an additional stress factor, which also led to a decrease in the metabolic efficiency of seed germination by 1.6-2.2 times. Thus, pre-germination treatment of P398 hybrid seeds with the JS bioregulator increased the negative impact

of non-optimal temperatures, which led to a phytotoxic effect manifested by a significant decrease in overall germination and critical metabolic disturbances.

The response to cold test in hybrid P465 was not as substantial as that of hybrid P398. Statistically insignificant changes in the lengths of embryonic roots and seedlings (Figure 6), as well as their vigor (Figure 7), were observed.

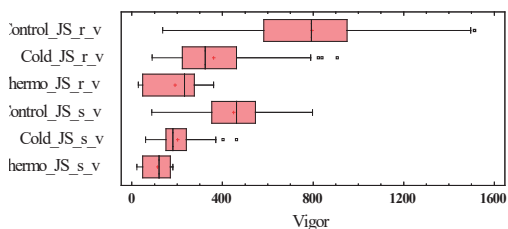


Figure 5. Root (r) and seedlings (s) vigor (v) of P398 corn hybrid pre-treated with bioregulator JS and germinated under different conditions

However, metabolic efficiency decreased by 26.12% relative to optimal conditions due to the redistribution of used reserve substances, the majority of which (58.24%) was used to provide energy for physiological processes and respiration.

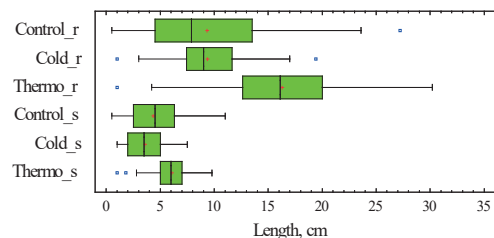


Figure 6. Root (r) and seedlings (s) length of P465 corn hybrid germinated under different conditions

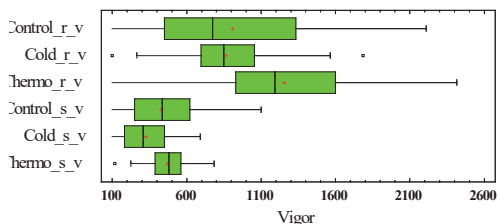


Figure 7. Root (r) and seedlings (s) vigor (v) of P465 corn hybrid germinated under different conditions

An analysis of data on the effect of elevated temperatures on the morpho-biological

characteristics of the dent hybrid P465 demonstrates its pronounced resistance to thermal stress (+50°C) compared to the flint hybrid P398. Hybrid P465 was shown to adapt and maintain basic life functions under heat stress. Better seed survival of P465 at high temperatures is confirmed by a moderate decrease in overall germination by 18% compared to optimal conditions. A key characteristic of the hybrid's high resistance is the length of roots and seedlings, which, on average, exceeded significantly ($p \leq 0.001$) the control seeds by 1.74-6.97 cm (Figure 6). In addition, it was noted that root and seedling vigor was 38.55% and 10.17% higher than in the control, respectively (Figure 7). This confirms the conclusion that intensive linear growth is a consequence of stress exposure. Furthermore, the dent hybrid demonstrated high metabolic plasticity, which enabled resource redistribution, reducing ineffective respiration (by 3.55%) and increasing overall metabolic efficiency (by 7.46%). The seeds rapidly and efficiently mobilize their reserve substances during germination, especially under stress. This made it possible to use reserve substances more effectively and purposefully for the development of a powerful root system. Thus, the P465 hybrid demonstrated significant resistance to heat stress. It maintained high germination, increased root and seedling vigor, and effectively managed its metabolic processes, demonstrating an adaptive response. Compared to the flint hybrid P398, the dent P465 hybrid is significantly better suited for cultivation in both low and high temperature conditions. Seeds of the P465 hybrid pre-treated with the bioregulator JS demonstrated metabolic efficiency 7.0% higher than in the control seeds (Figure 1). However, changes in root and seedling length and vigor were not significant. The increase in metabolic efficiency was due to increased root and seedling biomass. The use of the JS bioregulator for pre-germination treatment of seeds of the dent hybrid P465 under non-optimal temperatures had a positive effect on the restoration of physiological potential after abiotic stress (Figures 8, 9).

The bioregulator stimulated root growth and its vigor, which were significantly greater ($p \leq 0.001$) than those of control seeds. Seedling

length and vigor also tended to increase in cold test, and was significant ($p \leq 0.05$) in heat test. These data indicate that the combined effect of non-optimal temperatures and the JS bioregulator on the seeds of the P465 hybrid had a synergistic effect on the utilization of reserve substances to develop a strong root system without affecting seedling growth. Hybrid P465 demonstrates significantly improved tolerance to non-optimal temperatures and the combined effects of non-optimal temperatures and a bioregulator. Its ability to adapt and maintain vital functions under abiotic stress includes improved germination, dynamic root growth, and increased root vigor. This hybrid demonstrates high metabolic plasticity, effectively redistributing resources for survival. It is well known, that plants alter numerous phenotypic traits in response to environmental conditions, from the metabolic and cellular levels to the plant architecture level. This phenotypic plasticity is mediated by a combination of genetic and environmental factors and their interactions (Fu & Wang, 2023; Georgieva, 2025).

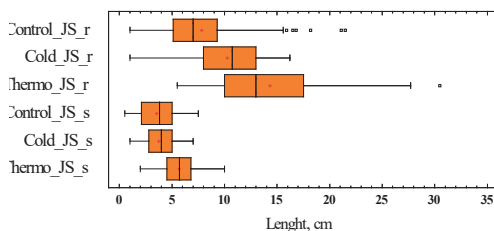


Figure 8. Root (r) and seedlings (s) length of P465 corn hybrid pre-treated with bioregulator JS and germinated under different conditions

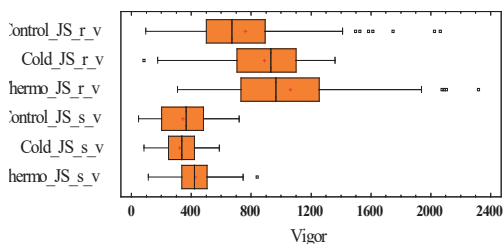


Figure 9. Root (r) and seedlings (s) vigor (v) of P465 corn hybrid pre-treated with bioregulator JS and germinated under different conditions

Thus, our results support the conclusion that the different hybrid responses to the application of non-optimal temperatures and JS

bioregulator were predetermined by the phenotypic plasticity of the corn hybrid.

One of the most important questions in plant stress biology is why the vast amount of knowledge about physiological and molecular responses to abiotic stresses has led to the development of so few climate-tolerant crop varieties (Verslues et al., 2023). Controlled stress experiments typically involve altering temperature, humidity, irrigation, light, or adding a chemical to modify the response to abiotic stress. Ideally, other environmental parameters are kept as stable as possible, so that only one or a combination of a few abiotic stresses occur simultaneously. Field trials do not represent a typical growing season that can be reproduced under standardized conditions. Even when temperature and precipitation are close to long-term averages, periods of extreme weather occur. In the field, some stressors are constantly present, such as rising night temperatures, nutrient deficiencies, salinity and heavy metals in the soil, but other stressors accumulate more gradually, such as drought, and can occur at any stage of development, with varying impacts on yield (Deng et al., 2016; Khalid et al, 2021; Verbraeken et al., 2021; Khaeim et al., 2022).

It should be noted that the 2025 growing season in the Republic of Moldova, when the field experiments were conducted, was characterized by a hot and dry August. These weather conditions resulted in a 9% reduction in corn yield compared to the decade average (Statistical yearbook..., 2025).

In this regard, we try to conduct a comprehensive analysis of the correlations between morpho-biological characteristics of corn growth under hypo- and hyperthermia and productivity. As noted above, the relevance of the study lies in the fact that the correlation between corn yield and its morpho-biological traits under normal and temperature stress conditions serves as a reliable criterion for selecting stress-resistant and high-yielding genotypes.

Data on the P398 hybrid confirm that in early stage of growth under non-optimal temperature the root and seedling lengths are not reliable predictors of final productivity (Table 1). Low correlation coefficients ($r=0.3634$ and $r=0.2295$) indicate that the genetic mechanisms of heat

and cold resistance at early stages and drought resistance during the flowering/filling period are regulated by different groups of genes.

According to the coefficient of determination (R^2), only 5.2-13.2% of the variability in field emergence is due to the potential for linear tissue growth under extreme temperature conditions. This indicates that the survival of the P398 hybrid in field conditions is determined not by the speed of growth processes, but probably by the biochemical stability of cellular structures or the efficiency of antioxidant systems (Pushkina & Kurchenko, 2016; Rao et al., 2025).

The established moderate-strength correlation ($r=0.5185$) between field emergence and embryonic root biomass at +10°C demonstrates that the survival of this genotype is determined not by the speed of linear cell elongation (Table 1), but by the intensity of morphogenesis and the formation of structural elements of the root system (the initiation of lateral roots and the thickening of axial roots).

Table 1. Correlation coefficients between laboratory characteristics of the P398 corn germination after temperature stress and field emergence and yield

Characteristics of P398	Temperature stress	Control seeds	
		Field emergence	Yield
Overall germination	Cold-test	-0.1681	0.3159
	Heat test	-0.0576	0.5364
Root length	Cold-test	-0.0298	0.5535
	Heat test	0.3634	0.2550
Seedlings length	Cold-test	0.2295	0.0374
	Heat test	0.0659	-0.3302
Root biomass	Cold-test	0.5185	-0.3949
	Heat test	-0.0450	-0.1157
Seedlings biomass	Cold-test	0.1933	0.4316
	Heat test	0.1367	0.4959

This hybrid demonstrates the high efficiency of mobilization and reutilization of endosperm reserves, aimed at the architecture of a morphologically and anatomically stable and functionally effective root system under limiting temperature conditions.

Therefore, when assessing the seed quality of the P398 hybrid, the key criterion for predicting field emergence and yield should be the weight of root biomass formed during cold testing, rather than their length or heat resistance. Research confirms that this hybrid excels due to the "quality" of its root system, not growth rate.

The significant positive correlation ($r=0.5535$) was found between yield and the length of the primary root system under cold test conditions (Table 1). This correlation indicates that yield potential is depended by the genotype's ability to develop roots at low positive temperature ($+10^{\circ}\text{C}$). Effective development of primary roots in the early stages not only ensures reliable plant anchorage of the plant in the soil, but also optimizes phosphorus absorption during long, cold spring conditions, determining future productivity (Khan et al., 2023).

The correlation ($r=0.5364$) between seed germination after exposure to heat test ($+50^{\circ}\text{C}$) and corn yield characterizes the high thermal stability of the hybrid's cell membranes and enzymatic systems. The ability of seeds to maintain viability after temperature shock serves as a reliable indicator of the organism's overall nonspecific resistance. This is a reliable indicator that the plant will withstand the August elevated temperatures.

The moderate correlation between yield and biomass expended on seedling growth under non-optimal temperatures ($r=0.4316$ and $r=0.4959$) indicates the importance of the metabolic plasticity (Table 1). Yield depends on how efficiently a hybrid converts endosperm reserves into its own tissues, without wasting energy on stress management. Efficient use of seed resources under extreme temperatures is a key criterion for selecting energy-efficient genotypes. Moreover, the weak correlation between yield and root length under hyperthermia ($r=0.2550$) confirms that tissue growth is less important for productivity in hot conditions than maintaining viability and dry matter accumulation (Körner, 2015; Salika & Riffat, 2021; Samat et al., 2025).

The extremely low correlation coefficients obtained in the experiment using seed treatment with the JS bioregulator (0.1453 for cold and 0.0650 for heat test) mean that after seed treatment, field emergence no longer depends on the intensity of seedling biomass accumulation (Table 2). The lack of strong correlation between germination and biomass at elevated temperatures indicates that the bioregulator works at the cellular level (membrane protection, synthesis of heat shock proteins or antioxidant defense system), and

not by stimulating growth processes (Wahid et al., 2007; Huot et al., 2014; Cannea & Padiglia, 2025; Rao et al., 2025; Samat et al., 2025).

After pre-sowing seed treatment with the JS bioregulator (Table 2), the relationship between field productivity and laboratory germination at low temperatures was strong ($r=0.6559$). This indicates that the bioregulator maximizes the genetic potential of the P398 hybrid specifically for cold conditions.

The low correlation between laboratory germination under heat test (50°C) and hybrid yield indicates the presence of a physiological aftereffect of the bioregulator. Probably, the bioregulator initiates mechanisms of pre-adaptation, shifting the metabolic vector toward mitigating the stress factors of early ontogenesis (in particular, cold resistance).

Thus, the realization of the crop's biological potential in field conditions is mediated not so much by the seeds' direct thermotolerance to heat stress, but by the induced systemic resistance established during the initial stages of germination. This allows to describe the effect of the studied bioregulator as a factor in the formation of cross-resistance, in which an increase in constitutive cold tolerance correlates with a general desensitization of the genotype to subsequent fluctuations in the hydrothermal regime during the growing season (Kanjevas et al., 2022).

Table 2. Correlation coefficients between laboratory germination characteristics of JS pre-treated the P398 corn after temperature stress and field emergence and yield of corn pre-sowing treated with JS

Characteristics of P398	Temperature stress	Seeds pre-treated with JS bioregulator	
		Field emergence	Yield
Overall germination	Cold-test	-0.4086	0.6559
	Heat test	-0.8283	0.2785
Root length	Cold-test	-0.6230	-0.1103
	Heat test	-0.5820	-0.2230
Seedlings length	Cold-test	-0.0220	-0.2726
	Heat test	-0.1815	-0.4961
Root biomass	Cold-test	-0.5391	-0.4503
	Heat test	-0.3259	-0.5170
Seedlings biomass	Cold-test	0.1453	-0.1622
	Heat test	0.0650	0.0750

Thus, under the influence of the bioregulator, a redistribution of the plant's adaptive resources occurs. Maximum mobilization of the P398

genetic potential shifts toward overcoming the initial temperature deficit, laying the foundation for stable biological productivity, regardless of subsequent extreme effects of hyperthermia. The productivity of the P398 corn hybrid in cold climates is largely determined not only by its genetic potential but also by the effectiveness of agricultural practices aimed at optimizing early development and mitigating the impact of low temperatures, where the use of bioregulators plays a key role.

An analysis of the relationships of morpho-biological characters of the P465 hybrid allowed us to verify the physiological profile of a "highly adaptive" type with a high thermotolerance threshold (Table 3). The deterministic relationship ($r=0.8230$) between laboratory germination under heat test ($+50^{\circ}\text{C}$) and field emergence demonstrates that thermal stability is a key predictor of the viability of this genotype. Such a strong correlation indicates that thermal tolerance mechanisms are the primary limiting factor in realizing the hybrid's biological potential. The relationship between the hybrid's field emergence and laboratory germination at 10°C was also significant ($r=0.6679$). This confirms the P465 hybrid is stress resistance to both temperature extremes, although heat resistance remains the dominant trait.

Unlike the P398 genotype, the P465 hybrid is characterized by a positive correlation between field emergence and biomass accumulation ($r=0.5657$) of seedling under heat test (Table 3). This relationship indicates the maintenance of active metabolism at critical temperatures. The hybrid demonstrates not only high survival at heat test, but also the ability to effectively morphogenesis. The formation of a full-bodied, physiologically vigorous seedling under thermal stress serves as a reliable biomarker of high field emergence and successful adaptation of this hybrid.

Thus, the heat test proved to be a comprehensive assessment method for P465 hybrid. This "energy-intensive" hybrid maintains high metabolic activity and biomass accumulation even under extreme heat. In unstable climates, P465 is the most reliable: its field survival is genetically determined through thermal protection mechanisms. This ensures stable

germination during both recurrent cold spells and abnormal heat waves.

However, despite its high heat resistance, the yield of the P465 corn hybrid is predetermined by completely different factors. A very strong, almost functional, relationship was found between corn yield and seedling length ($r=0.7408$) during germination in cold conditions (Table 3). The intensity of tissue elongation under low temperature is an "indicator of future yield". Seedlings that show a quick start in the cold form the most productive plants. The length of embryonic roots at low temperatures also correlates strongly with yield ($r=0.6389$), confirming that the foundation for P465 productivity is laid through early development of the cold soil. It should be noted that a very weak relationship ($r=0.2329$) was found between yield and overall germination at high temperatures (Table 3). This means that high seed thermotolerance is important only for survival, but it alone does not guarantee a high corn yield.

Table 3. Correlation coefficients between laboratory germination characteristics of the P465 corn after temperature stress and field emergence and yield

Characte- rists of P465	Temperature stress	Control seeds	
		Field emergence	Yield
Overall germination	Cold-test	0.6679	-0.3616
	Heat test	0.8230	0.2392
Root length	Cold-test	-0.1439	0.6389
	Heat test	-0.2661	-0.4558
Seedlings length	Cold-test	0.3431	0.7408
	Heat test	0.2638	-0.5502
Root biomass	Cold-test	-0.2354	-0.1655
	Heat test	-0.4555	-0.1320
Seedlings biomass	Cold-test	-0.6814	0.1519
	Heat test	0.5657	-0.4248

The P465 hybrid yield is formed not during the struggle against overheating, but during the period of effective growth at low temperatures. Thus, the P465 corn hybrid utilizes its exceptional thermotolerance as a preservation mechanism of population, but realizes its productivity potential through growth potential during the cold (starter) period.

The pre-sowing treatment of P465 seeds with the JS bioregulator reveals a clear hierarchy of factors determining sowing success and corn productivity (Table 4). The effect of JS bioregulator on growth and the biomass utilized

for germination drives hybrid survival. This effect results in a highly significant correlation between field emergence and the seedling length ($r=0.8086$). Unlike untreated seeds, emergence of pre-treated seeds directly depends on the ability of the seedlings to rapidly elongate at cold test, allowing the plant to more quickly penetrate the soil layer during cold spring weather. The amount of biomass utilized by the seedlings for germination during cold conditions plays a decisive role in field emergence ($r=0.8142$). It turned out that 66% (R^2) of field emergence is determined by the amount of seedling biomass gained at low temperatures. This means that the bioregulator promotes the mobilization of seed resources for germination. The correlation between field emergence and overall germination at heat test remains maximal ($r=0.8100$), confirming the genetic reliability of the P465 hybrid and its thermal stability, meaning that the seeds are guaranteed to survive when the heat shock has passed (Table 4). The correlation between field emergence and root biomass in the cold test was quite significant ($r=0.5286$), while the correlation with root length was weak ($r=0.2282$). This fact confirms that the bioregulator stimulates root "quality" (thickness, branching, weight), rather than simple root elongation.

Table 4. Correlation coefficients between laboratory germination characteristics of JS pre-treated the P465 corn after temperature stress and field emergence and yield of corn pre-sowing treated with JS

Characteristics of P465	Temperature stress	Seeds pre-treated with JS bioregulator	
		Field emergence	Yield
Overall germination	Cold-test	-0.4770	0.3413
	Heat test	0.8100	-0.6185
Root length	Cold-test	0.2282	0.0159
	Heat test	0.1573	0.1542
Seedlings length	Cold-test	0.8086	-0.3899
	Heat test	0.3778	-0.5352
Root biomass	Cold-test	0.5286	-0.1718
	Heat test	-0.0298	0.3317
Seedlings biomass	Cold-test	0.8142	-0.3798
	Heat test	0.6370	-0.3083

It should be noted, that under hyperthermia, temperature (+50°C) acts as a strict "filter" for viability. Furthermore, the realization of germination potential directly correlates with

the efficiency of mobilization seed reserve substances into seedling biomass ($r=0.6370$). Thus, while growth rate is the limiting factor under cold conditions, under heat conditions, it is overall physiological stability and the energy resource for germination.

Unlike field emergence, the yield of P465 hybrid demonstrates a weak dependence on most laboratory characteristics (Table 4). Weak correlations between productivity and root length and biomass under both non-optimal temperature conditions of germination.

Thus, the use of the JS bioregulator on the P465 corn hybrid transforms the architecture of correlation relationships, shifting the focus of root and seedling quality control. The key predictor of field emergence is the length and biomass of root and seedling under cold test conditions: high initial growth rates guarantee the formation of optimal plant density. A notable decrease in the correlation between laboratory tests and hybrid yield indicates that the JS bioregulator effectively mitigates initial stress risks, resulting in the productivity being determined more by growing conditions and agricultural practices than by the initial stress tolerance of the seeds.

CONCLUSIONS

Both hybrids studied demonstrate the response reaction to influence of low and high temperatures, but exhibit varying degrees of resilience. The hybrid P465 significantly outperformed the P398 hybrid in its ability to survive and growing stronger, more vigorous roots and seedlings, especially under elevated temperature. The bioregulator JS is a powerful modifier of seed germination characteristics and adaptive responses, but its effect depends on genotype and growth conditions. Applying the JS bioregulator to seed of the dent hybrid P465 before germination at non-optimal temperatures had a positive effect on restoring physiological potential after abiotic stress. However, for the flint hybrid P398, the combined effect of non-optimal temperatures and the bioregulator JS significantly reduces ($p \leq 0.001$) the vigor of roots and seedlings.

Analysis of correlations between key morphobiological parameters and productivity allows for differentiated hybrid selection strategies

based on predicted agroclimatic risks and bioregulator use. The use of the bioregulator mitigates the rigid dependence of germination and growth intensity on abiotic factors, making both hybrids more adaptive.

Hybrid Porumben 398 (flint) is characterized by moderate endogenous cold tolerance of the root system and pronounced growth depression under abiotic stress. In this case, treatment with the bioregulator not only mobilizes germination potential in low-temperature environments but also creates resistance at the early stages of development.

Hybrid P465 (dent) exhibits as highly adaptive genotype with pronounced genetic heat resistance and metabolic plasticity. For this hybrid, the bioregulator acts as a resource accumulation engine. The bioregulator switches the hybrid to a high metabolic plasticity mode, with field germination becoming 66% dependent on the amount of biomass accumulated by the seedling at +10°C. The bioregulator promotes not only the hybrid's survival in hot weather, which is genetically determined, but also growth during the cold period through the efficient processing of endosperm reserves.

ACKNOWLEDGEMENTS

Research was carried out within the Subprogramme 011101 “Genetic and biotechnological approaches to agroecosystem management under climate change conditions” for 2024-2027, financed by the Ministry of Education and Research of the Republic of Moldova.

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