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THE INFLUENCE OF THE BARIUM COORDINATIVE COMPOUND ON THE MORPHO-PHYSIOLOGICAL DEVELOPMENT OF SOME HIGHER PLANTS

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In the current work, the main objective was to evaluate the effect of seminal and foliar treatments of a new barium-coordinating compound $[BaCoL_3(\mu\text{-}NCS)_2(NCS\text{-}\kappa N)_2]$ – CCBa on the growth and development of important agricultural species. In laboratory experiments the physiologically optimal concentration of CCBa solution was determined. The barium-coordinating compound has a beneficial effect on plants, but only at very low concentrations, in particular 0.001%. Its efficiency exceeds that of barium chloride ($BaCl_2$) treatments, having a significant positive impact on vegetative growth and plant water status, including under drought conditions. Under moisture deficit conditions, water status parameters in plants treated with CCBa were maintained at a more stable level compared to those treated with BaCl2, and especially compared to untreated plants.

Keywords: *CCBa, germination, growth, physiological processes, drought, higher plants*.

INFLUENȚA COMPUSULUI COORDINATIV AL BARIULUI ASUPRA DEZVOLTĂRII MORFO-FIZIOLOGICE A UNOR PLANTE SUPERIOARE

În lucrarea curentă obiectivul principal a constat în evaluarea efectului tratamentelor seminale și foliare a unui nou compus coordinativ cu bariu $[BaCoL_3(\mu\text{-}NCS)_2(NCS\text{-}\kappa N)_2]$ – CCBa asupra creșterii și dezvoltării unor specii agricole importante. În experiențele de laborator a fost determinată concentrația fiziologică optimă a soluției CCBa. Compusul coordinativ cu bariu are un efect benefic asupra plantelor, însă doar la concentrații foarte scăzute, în special 0,001%. Eficiența acestuia o depășește pe cea a tratamentelor cu clorură de bariu ($BaCl_2$), având un impact pozitiv semnificativ asupra creșterii vegetative și statusului hidric al plantelor, inclusiv în condiții de secetă. În condiții de deficit de umiditate s-a constatat, că parametrii statusului apei, la plantele prelucrate cu CCBa se mențin la un nivel mai stabil comparativ cu cele tratate cu $BaCl_2$, și în special, cu cele neprelucrate.

Cuvinte-cheie*: CCBa, germinație, creștere, procese fiziologice, secetă, plante superioare.*

INTRODUCTION

Coordination compounds represent a class of chemical substances that influence various physiological processes in cultivated plants [1-3]. The inclusion of different chemical elements in the composition of the complexes can essentially influence the manifested properties [4].

Barium is a very commonly occurring element in the Earth's crust, ranking 14th in terms of abundance. Due to its extensive use in various industrial processes, human activities play a significant role in the dispersion of barium into the environment. Thus, in many areas, barium levels detected in air, water, and soil can exceed natural values [5].

This chemical element in different concentrations is present in all plant organs, being absorbed from the soil. Increased amounts of barium can be found in soil, food, nuts, seaweed, fish, etc. However, the amount of barium that is detected in food and water is not high enough to become a health problem. In the human body, there are approximately 22 mg of barium. Daily consumption through food is around 0,75 mg. Barium is concentrated in the skeleton (20 mg), and smaller amounts are found in the pigment and iris of the eyes. In metabolism, it behaves similarly to Ca and Sr. The toxic dose is 200 mg, and the lethal dose – 3,7 g [6].

Barium is a toxic chemical element, but its toxicity is reduced due to its low bioavailability. In the human body, barium substitutes calcium in cells – this is a mechanism of its toxic effect. Excessive intake of barium in the human body can be associated with the consumption of vegetables and fruits grown in a region with a high barium content in the soil. In such situations, barium begins to seriously compete with calcium in the bones, replacing it, which leads to the development of a severe calcium deficiency in the body and, respectively, with the associated consequences – osteoporosis, joint diseases, skeletal deformities, etc. However, barium sulfate suspension is used in medical practice, since barium absorbs X-rays well – it is sometimes used to increase contrast. However, the administration of barium sulfate before an X-ray of the gastrointestinal tract does not cause any harm to the human body for a very simple reason: barium sulfate is insoluble in water and, therefore, cannot be absorbed by the body. Despite this fact, in cases of poisoning, barium is difficult to eliminate from the human body [7].

In higher plants, the background content of barium varies between 0.01 and 250 mg/kg dry mass, reaching the highest values in the leaves of cereals and legumes and, respectively, the lowest values in fruits and seeds. The absorption of this chemical element by the root system is related to both convective transfer and exchange diffusion. Its consumption depends largely on the reaction of the environment: with acidification, this process increases, and alkalization, on the contrary, limits it. In metabolic processes, barium behaves like calcium. When administered in low concentrations, this element stimulates early physiological processes by increasing germination energy and emergence rate, while also contributing to higher fruit yield and improved biochemical composition, particularly in terms of sugar and ascorbic acid content. However, under conditions of excessive accumulation of barium in plant tissues, of approximately 220-250 mg/kg of dry mass, signs of phytotoxicity appear: dwarf plants have discolored leaves, and crop productivity is considerably reduced [8].

Studies conducted by internationally recognized researchers have shown that barium does not have a negative effect on cucumber seed germination; on the contrary, in certain concentrations, the germination rate was even high. Treatment with Ba caused variations in the activity of antioxidant enzymes in different organs of *Cucumis sativus* L. plants, particularly stimulating catalase activity in leaves and mature stems. Similar results have been reported in *Glycine max* (L.) Merr., where an increase in catalase activity was observed under barium-induced stress conditions [9]. High doses of Ba caused an intensification of the activity of the enzyme glutathione peroxidase in both young and mature leaves, as well as in stems. According to Yang and Poovaiah (2002), this enzymatic stimulation is correlated with the accumulation of hydrogen peroxide and calcium ions (Ca^{2+}) in the cells [10]. The application of high concentrations of Ba led to the inhibition of dry biomass formation, especially in the aerial organs of the plants. A high capacity for barium accumulation was also observed in the roots and shoots of cucumber plants. The oxidative stress caused by Ba was evidenced by the activation of the antioxidant enzyme system, including catalase, glutathione peroxidase and ascorbate peroxidase [11].

However, the influence of barium on plant development and growth remains insufficiently researched. This study was designed to evaluate the effect of the coordination compound of Ba on higher plants. Starting from this premise, *the purpose of the present study* is to evaluate the effect of the compound $[BaCoL_3(\mu\text{-}NCS)_2(NCS\text{-}\kappa N)_2]$ (CCBa) [12] on higher plants (*Solanum lycopersicum* L., *Zea mays* L., and *Triticum aestivum* L.).

The barium coordination compound under study has previously been investigated on lower organisms, with the aim of evaluating its influence on the productivity of the cyanobacterial culture *Spirulina platensis* (Nordst.) Geitl – CALU – 835. Research has shown that the effect of CCBa is dependent on the administered concentration and manifests a positive impact on the accumulation of spirulina biomass, at moderate doses. Optimal concentrations significantly stimulated spirulina growth, while higher doses had an inhibitory effect [13].

Materials and methods

Experimental research was carried out in the laboratory „Genetics, Physiology and Biochemistry of Plants" within the „Ion Creanga" State Pedagogical University of Chisinau. In laboratory experiments,

under optimal conditions and water stress, the effect of seminal and foliar treatment of aqueous solutions of barium chloride (prototype) and the coordination compound of barium on the growth and development of *Triticum aestivum, Solanum lycopersicum* and *Zea mays* plants was verified (Fig. 1).

The following varieties and hybrids of plants approved in the Republic of Moldova served as the study objects: tomato, variety Rio Grande; corn, hybrid SY Ulises; wheat, variety Renan.

Rio Grande tomatoes are an early variety with high productivity. The plum-like fruits, weighing 110-115 g, have an intense red color and are distinguished by excellent taste and good transportability. This variety has moderate resistance to verticillium wilt, alternating stem cancer and late blight. It is recommended for cultivation in open ground and can be planted both through seedlings and seeds. It is ideal for fresh consumption and for processing.

SY Ulises corn is a semi-early hybrid with high tolerance to spring temperature variations. The plants are medium to tall and provide exceptional yields, both under medium and intensive technology conditions. It is characterized by good yields even under heat and water stress. This hybrid has disease tolerance and superior grain quality.

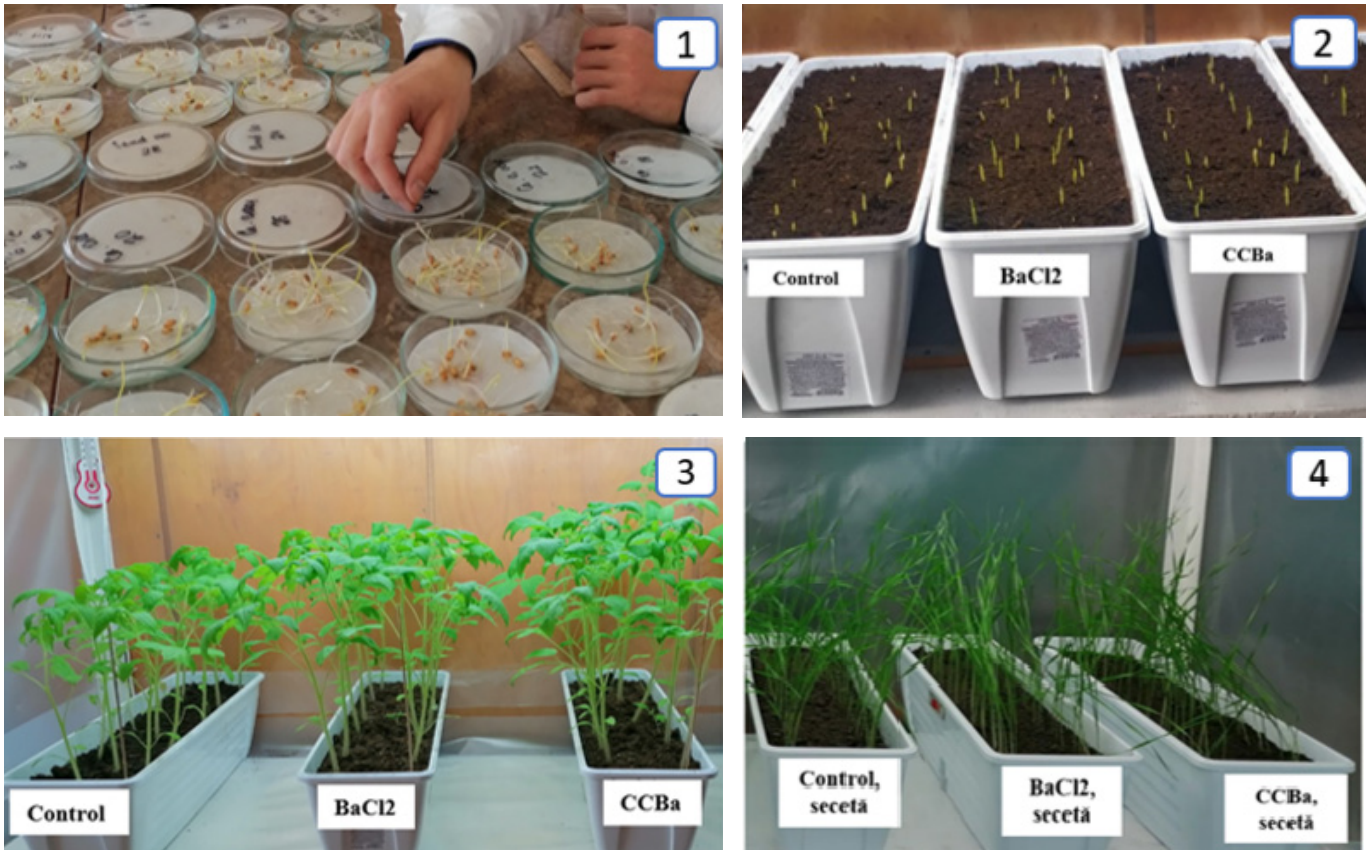

Figure 1. Sequences from the experiences carried out: 1 – germinated wheat seeds; 2 – germination and emergence of corn seedlings on the soil surface; 3 – tomato plants grown under optimal conditions; 4 – wheat plants subjected to drought

Renan wheat is a semi-early, aristate variety with medium-height plants and robust stems. This variety is considered an “improvement wheat” or “strength wheat” due to the superior quality of the bread produced from it. It performs well in difficult wintering conditions and has good resistance to lodging. Under normal cultivation conditions, the gluten content varies between 26 and 32%. The recommended sowing density is 370-400 grains per square meter, and sowing should be done at the beginning of the optimal period. It is a wheat variety with excellent quality for baking.

In laboratory experiments, plants were grown in pots with a capacity of 10 kg of dry soil and controlled light and humidity conditions. During vegetative growth, the seeds and the leaf apparatus of the plants were treated with the substances under study. The duration of water stress was 7 days.

Determined indices: linear stem growth, aboveground biomass accumulation, leaf area, water status parameters (total water content, saturation deficit and water retention capacity).

The initial objective of the study was to identify the physiologically optimal concentration range of the aqueous solution of CCBa. For this purpose, experiments were set up that included the following variants: 1st *variant* – control, seedlings grown from seeds treated with water; 2nd *variant* – seedlings grown from seeds treated with 0,1% Ba coordination compound; 3rd variant – seedlings grown from seeds treated with 0,01% Ba coordination compound; 4th *variant* – seedlings grown from seeds treated with 0,005% Ba coordination compound; 5th *variant* – seedlings grown from seeds treated with 0,001% Ba coordination compound; 6th *variant* – seedlings grown from seeds treated with 0,0001% Ba coordination compound.

Another *objective* of the research was to evaluate the influence of the coordination compound with barium on the growth and development of tomato and corn plants under optimal conditions. For this purpose, experiments were set up with tomato and corn, which included the following variants: 1st *variant* – control, seeds and plants treated with water; 2nd *variant* – seeds and plants treated with barium chloride; 3rd *variant* – seeds and plants treated with coordination compound with Ba.

A *third objective* aimed to investigate the effect of the barium coordination compound on the growth and development of wheat plants subjected to moderate drought stress. For this purpose, experiments were set up with variants: 1st *variant* – control, seeds and plants treated with water; 2nd *variant* – seeds and plants treated with barium chloride; 3rd *variant* – seeds and plants treated with the Ba coordination compound. Some of the plants in each variant were exposed to a water stress regime, achieved by reducing the water supply, while the rest were maintained under optimal humidity conditions. The duration of the water stress was 7 days. Subsequently, physiological parameters were determined, such as the total water content in the leaves, the saturation deficit, the water retention capacity after 2 hours of dehydration and the height of the plants.

Results and discussions

In order to establish the physiologically optimal concentration of the CCBa solution, laboratory experiments were conducted to stimulate/inhibit the initial development of seedlings. To achieve this objective, laboratory experiments were organized in which several concentrations of the CCBa solution were tested on wheat seeds and seedlings, respectively: 0,1%, 0,01%, 0,005%, 0,001% and 0,0001%. The data obtained were analyzed in comparison with the untreated control.

The results obtained by applying these concentrations to wheat seeds were analyzed according to their impact on the length of the embryonic organs (root and coleoptile), the total length of the seedling, as well as the accumulated biomass (Table 1). The data indicate significant variability in the physiological response of seedlings depending on the applied concentration.

Following the analysis of the results obtained from laboratory experiments on the influence of the barium coordination compound on the growth and development of wheat seedlings, it was found that its effect varies significantly depending on the concentration. The study followed the changes in the length of the seedling organs (radicle, coleoptile and total length), as well as in their biomass, compared to the untreated control.

Table 1. Identification of the physiologically optimal concentration of CCBa solution on the growth and development of wheat seedlings

Variants		Control 0,1	Barium coordination compound, %				
			0,01	0,005	0,001	0,0001	
Indicators		M ± m Δ, % M	M ± m Δ, % M	M ± m Δ, % M	M ± m Δ, % M	M ± m Δ, % M	M ± m Δ, % M
Length, mm	radicle	55,7±1,03	27,7 ± 0,81 **-50,27**	38,5 ± 0,49 **-30,88**	78,3 ± 2,03 **40,57**	76,7 ± 1,71 **37,70**	56,5 ± 1,24 **1,44**
	coleoptile	47,3±0.26	19,1 ± 0,36 **-59,62**	36,1 ± 0,64 **-23,68**	48,9 ± 1,58 **3,38**	54,9 ± 0,72 **16,07**	49,8 ± 0,94 **5,29**
	seedling	103,0 ±1.24	46,8 ± 0.59 **-54,56**	74,6 ± 0,57 **-27,57**	127,2 ± 1,81 **23,50**	131,6 ± 1,22 **27,77**	100,3 ± 1,09 **-2,62**

Biomass, g	**radicle**	0,35 ±0,005	0,14 ± 0,002 **-60,00**	0,28 ± 0,005 **-20,00**	0,42 ± 0,010 **20,0**	0,47 ± 0,009 **34,29**	0,40 ± 0,008 **14,29**
	coleoptile	0,46 ±0,014	0,22 ± 0,004 **-52,17**	0,34 ± 0,007 **-26,09**	0,51 ± 0,012 **10,87**	0,53 ± 0,012 **15,22**	0,45 ± 0,009 **-2,17**
	seedling	0,81±0,010	0,36 ± 0,003 **-55,56**	0,62 ± 0,006 **-23,46**	0,93 ± 0,011 **14,86**	1,00 ± 0,010 **23,46**	0,85 ± 0,009 **4,94**

At the radicle level, the best results were recorded at concentrations of 0,005% and 0,001%, where an increase of 40,57% and 37,70% was observed compared to the control, respectively. High concentrations, of 0,1% and 0,01%, had a strong inhibitory effect, reducing the radicle length by up to 50%. The same pattern was observed in the case of the coleoptile, where the concentration of 0,001% generated an increase of 16,07%, while 0,005% produced a slight positive effect (3,38%). The concentration of 0,1% proved to be toxic, causing a drastic reduction in the length of the coleoptile by almost 60%.

Regarding the total length of the seedling, the best results were also obtained in the concentrations of 0,001% and 0,005%, with increases of 27,77 and 23,5%. These data suggest that at low concentrations, CCBa strongly stimulates seedling elongation, whereas at higher concentrations, seedling development is significantly inhibited.

Biomass analysis showed the same trends. Radicle biomass increased by 34.29% at 0.001% and by 20% at 0.005%, while at 0.1% it decreased by 60%. Similarly, coleoptile biomass was stimulated at low concentrations, with an increase of 15.22% at 0.001%, but was drastically reduced at high concentrations. Total seedling biomass followed the same pattern, with the maximum effect recorded at 0.001%, with an increase of 23.46% compared to the control, while at 0.1% a reduction of over 55% was observed.

Therefore, the barium coordination compound has a stimulating effect on the growth and development of wheat seedlings only in very low concentrations. The concentration of 0.001% proved to be physiologically optimal, determining the best results both in terms of the length of the seedling organs and the accumulated biomass. Higher concentrations become phytotoxic and affect the development of the seedlings. These results highlight the importance of rigorous dosing in the use of coordination compounds in experimental phytotechnical treatments.

Another *objective* was to study the effect of the Ba coordination compound on the growth and development of tomato plants under optimal conditions. The data obtained highlighted a positive impact of this compound on the growth and development of tomato and corn plants (Table 2).

Table 2. Influence of the barium coordination compound (0.001%) on the growth and development of tomato and corn plants

variants	Plant height, cm		Biomass, g				Leaf surface, cm²	
		leaves		stem				
	M ± m	Δ, %M	M ± m	Δ, %M	M ± m	Δ, %M	M ± m	Δ, %M
Nightshade lycopersicum L., variety Rio Grande								
Control, H_2O	26.30±0.19		2.27±0.05		5.12 ± 0.14		125.24±1.61	
$BaCl_2$	30.92±0.31	17.57	2.84±0.02	25.11	6.59 ±0.17	28.71	151.17± 2.92	20.70
CCBa	34.58±0.27	31.48	3.08±0.04	35.68	7.36 ±0.21	43.75	168.31±2.13	34.39
Zea mays L., hybrid SY Ulises								
Control, H_2O	61.14±0.61		3.39±0.09		3.62 ±0.03		119.75±0.42	
$BaCl_2$	65.36±0.84	6.90	3.66±0.03	7.96	3.87±0.09	6.91	127.01±0.61	6.06
CCBa	67.28±0.49	10.04	4.02±0.04	18.58	4.17±0.06	15.19	143.12±0.34	19.52

Compared to the control variant, the treatment with CCBa caused a visible increase in plant height, leaf and stem biomass, as well as leaf area. In the tomato variety Rio Grande, it was found that the application of the coordination compound of Ba stimulated plant development, both compared to those in the control variant and the $BaCl_2$. The treated plants showed a more robust stem, more developed leaves and an extended leaf area, indicating a high photosynthetic capacity and a higher primary productivity potential. Increasing leaf area plays an important role in crop formation, as it allows dry matter accumulation during the "panicle-flowering" and "grain formation" stages. This contributes to increasing crop value by optimizing water use and helps reduce the amount of water lost through transpiration.

Also, in the case of corn plants, the SY Ulises hybrid, the compound stimulated vegetative development, leading to plant height growth, greater biomass accumulation and an increase in leaf area. The effects were more pronounced than in the case of $BaCl_2$, suggesting that the chemical structure of the coordinating compound favors more efficient assimilation and superior metabolic stimulation.

The results obtained demonstrate the potential of using CCBa as an effective biostimulator, contributing to optimizing the growth of corn and tomato plants under controlled conditions.

The third objective was to study the effect of the coordination compound with Ba on the growth and development of wheat plants under moderate drought conditions. In laboratory experiments, under optimal conditions and water stress, the effect of seminal and foliar treatment with barium chloride solutions and the coordination compound of barium on the growth and development of wheat plants, the Renan variety, was verified (Fig. 2).

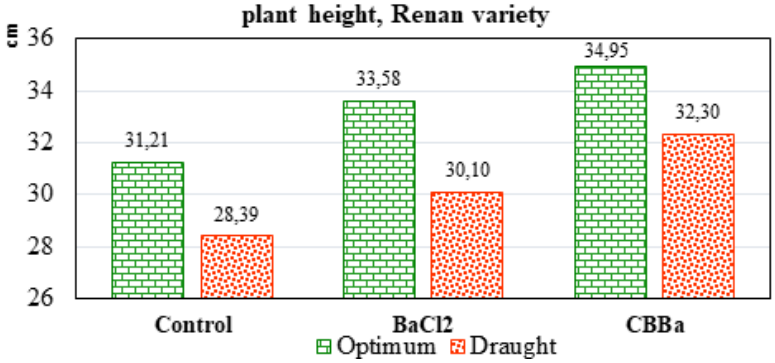

Fig. 2. Influence of CCBa on plant height of *Triticum aestivum*, Renan cultivar

It was found that, both under optimal moisture conditions and under drought, the treated plants were characterized by higher absolute values of the studied parameters compared to the untreated plants. Unfavorable water supply conditions lead to a different response in plant height in those treated with the studied compounds. Thus, an increase in the height of plants treated with CCBa is recorded compared to untreated plants, grown under the same drought conditions.

In laboratory experiments, the effect of barium chloride and a barium coordination compound on water status parameters – reflecting the water condition in the leaves of wheat plants (Renan cultivar) – was investigated during the early stages of ontogeny under water stress conditions (Table 3).

Table 3. Influence of FAS at the initial stages of ontogenesis on water status parameters in the leaves of wheat plants, Renan variety, under water stress conditions

Variants	Humidity	Water content, g · 100 g sq m		Saturation deficit, % from full saturation		Water retention capacity, water remaining for 2 h, % of initial turnover	
		M ± m	Δ, %M*	M ± m	Δ, %M*	M ± m	Δ, %M*
Control	optimum	85.81 ±1.2		3.92 ±0.08		70.80 ±0.5	
	drought	79.55 ±1.3		31.20 ±0.46		73.32 ±1.3	
$BaCl_2$	optimum	85.75 ±0.9		4.00 ±0.12		75.37 ±0.9	
	drought	80.64 ±0.7	1.37	28.46 ±0.75	-8.78	75.45 ±0.7	2.91
Barium coordination compound	optimum	86.19 ±1.1		3.89 ±0.06		75.69 ±0.3	
	drought	82.10 ±0.5	3.21	23.18 ±0.28	-25.71	79.28 ± 0.8	8.13

* - *compared to control plants under drought conditions*

Based on the data obtained, it can be observed that under optimal conditions, the water content in plant leaves is similar between all studied variants, with high absolute values of 85.75-86.19 g of water per 100 g of fresh mass, which indicates optimal tissue hydration.

Under moderate drought conditions, all variants register a decrease in water content compared to the optimal state, reflecting the impact of water stress on the water reserve in the leaves. However, plants treated with the coordination compound of barium show the lowest percentage decrease in water content, respectively, a relative increase of 3.21% compared to the control under drought conditions, which suggests a better water retention capacity and, implicitly, a higher tolerance to water deficit. The variant with $BaCl_2$ shows a moderate, but lower increase compared to CCBa, indicating that this treatment has a less pronounced effect on maintaining hydration under stress conditions.

Under drought conditions, the application of the Ba coordination compound contributed to maintaining a higher level of relative humidity of the leaves and water retention capacity, compared to the control plants, which suggests an improvement in the mechanisms of physiological adaptation to water deficit. A pronounced reduction in the saturation deficit was also observed compared to the control, indicating an increased efficiency of the leaves in maintaining internal water balance. Compared to the plants in the $BaCl_2$, those treated with CCBa recorded a more obvious increase in the water retention capacity after 2 hours of dehydration, which can be explained by its more stable and efficient action on cellular metabolism and membrane structure. This ability to reduce water losses and conserve water resources in tissues is essential for drought tolerance in the early stages of ontogenesis.

The main purpose of the study was to investigate the effect of the barium coordination compound on the growth and development of wheat, corn and tomato plants, as well as to evaluate its ability to modulate the physiological response of plants under optimal conditions and moderate water stress. The results obtained indicate that the treatment with CCBa, in low concentrations of 0.001%, has a biostimulatory potential, manifested by improving the growth parameters and water status of plants, compared to the plants in the control variants and those treated with barium chloride. However, in this study, no analyses were performed to determine the level of barium accumulation in plant tissues, an essential aspect for the evaluation of possible phytotoxic effects and for assessing the safety of using this compound in agricultural practice. Thus, additional research is needed to elucidate the toxicological potential of CCBa and to establish the application limits under technological conditions.

Conclusions

1. The compound $[BaCoL_3(\mu\text{-}NCS)_2(NCS\text{-}\kappa N)_2]$ exerts a beneficial effect on the growth and development of wheat seedlings only when used in very low concentrations. In particular, the concentration of 0.001% was shown to be physiologically optimal, leading to the best results in terms of both the length of the seedling organs and the accumulated biomass. On the other hand, higher concentrations have toxic effects on the seedlings, inhibiting their development.

2. Under optimal conditions, the application of CCBa treatments at the optimal concentration of 0.001% resulted in a significant increase in plant height, biomass and leaf area in the Rio Grande tomato variety and the SY Ulises corn hybrid, exceeding both the control and $BaCl_2$.

3. Under moderate drought conditions, treatment of seeds and plants with CCBa favored the maintenance of a higher water content in leaves compared to plants in the control and $BaCl_2$, reflecting a superior water retention capacity and a reduction in saturation deficit.

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