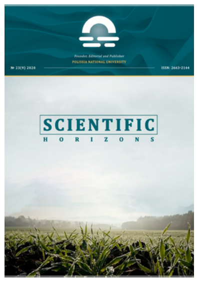
SCIENTIFIC HORIZONS

Journal homepage: https://sciencehorizon.com.ua

Scientific Horizons, 28(1), 61-72



UDC 631.811.98:635.656

DOI: 10.48077/scihor1.2025.61

Influence of biostimulants on physiological processes, productivity, and quality of pea crop in modern agriculture

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Article's History:

Received: 29.04.2024

Revised: 19.11.2024

Accepted: 30.12.2024

Abstract. The purpose of this study was to investigate the effects of biostimulants on increasing the adaptive mechanisms of pea (*Pisum sativum* L.) under water deficit conditions, with an emphasis on optimising physiological functions, biochemical processes, and morphological development of plants. The experiment was conducted

Suggested Citation:

Nebaba, K., Khmelianchyshyn, Yu., Panasiuk, R., Puczel, J., & Koberniuk, O. (2025). Influence of biostimulants on physiological processes, productivity, and quality of pea crop in modern agriculture. *Scientific Horizons*, 28(1), 61-72. doi: 10.48077/scihor1.2025.61.

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under controlled conditions that helped to accurately model the effect of water stress. The study used comprehensive evaluation methods, including physiological parameters (photosynthetic activity, transpiration), biochemical markers (antioxidant enzyme activity, proline level), and morphological parameters (length and weight of the root system). The findings confirmed that treatment with biostimulants significantly increased the adaptive potential of plants. Photosynthetic activity in the treated plants was 82%, which was substantially higher than in the control group, where this level reached only 60%. Transpiration in the treated plants stayed stable, ensuring optimised water balance even under stress. Biochemical analysis showed that the activity of superoxide dismutase and catalase in plants treated with biostimulants increased by 145% compared to control plants, which contributed to a major reduction in oxidative stress. The level of proline, as a key osmotic regulator, was also significantly higher in the treated plants, which maintained the stability of the cellular water balance. Morphological studies revealed that the plants treated with biostimulants had a more developed root system: the length of the roots was 10 cm longer, while the weight was greater than in the control. This helped the plants to use moisture from deeper soil layers, which improved their resistance to drought. As a result, the yield loss in the treated plants was half that of the control group. These findings highlighted the effectiveness of using biostimulants to increase pea resistance to water deficit and maintain productivity. This makes the proposed approach promising for implementation in agricultural technology, especially in arid regions where water deficit is the primary limiting factor for crops

Keywords: plant adaptation; abiotic factors; stress resistance; transpiration; water balance

INTRODUCTION

In the context of global climate change, accompanied by more frequent droughts and unstable water supplies, there is a growing need to develop effective methods for adapting crops to stressful conditions. Pea is a valuable crop for food security due to its rich protein content and ability to fix atmospheric nitrogen, which helps improve soil fertility. However, this crop is quite sensitive to water shortages, which greatly limits its productivity in arid regions. The relevance of this study is driven by the need to optimise pea production under drought conditions, which is a major challenge for the agricultural sector in Ukraine and other countries with comparable climatic conditions. Currently, there are a limited number of studies that comprehensively investigate the effect of biostimulants on the physiological, biochemical, and morphological adaptation mechanisms of pea.

The principal problem is that conventional pea cultivation technologies are not effective enough to reduce the effects of abiotic stresses, specifically water deficit (Drobitko *et al.,* 2024). Existing approaches, such as optimising irrigation or fertilisation regimes, have a limited impact on maintaining the physiological stability of plants under stressful conditions. At the same time, the mechanisms underlying plant adaptation to water stress, such as regulation of transpiration, activation of antioxidant defences, and improvement of osmotic balance, are still understudied in the context of practical applications (Krychkovska *et al.*, 2024).

E. Szpunar-Krok (2022) investigated the effect of foliar application of biostimulants on the physiological response of peas. The researcher found that such preparations help maintain photosynthetic activity, reduce water loss through leaves, and improve yields under conditions of limited water supply. This emphasised the significance of the effects of biostimulants on basic physiological processes. S.A. Ismaiel *et al.* (2022) focused on the relationship between biostimulants, soil characteristics, and pea yield in the field. In their study, the researchers showed that biostimulants not only increase plant resistance to stress factors but also improve the physical and chemical properties of the soil, creating optimised conditions for growth. A.M. Castiglione *et al.* (2021) highlighted the role of microbial biostimulants in modern agriculture. The researchers noted that such preparations can improve plant resistance to abiotic stresses by stimulating the synthesis of metabolites involved in the regulation of the stress response. A. Kocira *et al.* (2020) analysed changes in biochemical parameters and yield of beans after the application of biostimulants. The researchers demonstrated the positive effects of the preparations on protein content, regulation of nitrogen metabolism, and overall plant yield.

A.F. El Sheikha *et al.* (2022) focused on the effects of biostimulants on the growth and nutritional quality of legumes. The findings indicated an increase in yield and improvement in the nutritional value of beans due to the use of biostimulants, which makes these products a valuable tool for sustainable agriculture. W. Biel *et al.* (2023) investigated the effects of amino acid biostimulants in combination with nitrogen fertilisation and irrigation on the composition of pea seeds. The researchers' findings confirmed the considerable effects of these factors on the energy value of seeds and overall plant productivity. S. Naz *et al.* (2023) investigated the use of seaweed extracts to stimulate pea growth. The researchers showed that such biostimulants increase plant productivity by improving physiological indices such as photosynthetic efficiency and biomass accumulation. F.A. Youssef *et al.* (2024) analysed the effects of combined use of organic and mineral fertilisers in pea cultivation. The researchers noted that organic biostimulants can compensate for the negative effects of water deficit, ensuring stable growth and yield.

R. Johnson *et al.* (2024) considered biostimulants as a promising tool for increasing crop productivity and resistance to abiotic stress. The researchers focused on the possibilities of integrating biostimulants into sustainable agriculture strategies. L. Nephali *et al.* (2020) applied a metabolomic approach to analysing the effects of biostimulants in their study. The study demonstrated that these preparations activate metabolic pathways that contribute to plant adaptation to stressful conditions such as drought. Despite considerable progress in the study of the effects of biostimulants, there are important aspects that are still understudied. The molecular mechanisms of action require deeper analysis, including the role of signalling pathways and genetic regulation of stress adaptation. The effects of biostimulants under conditions of multi-stress factors, such as a combination of drought and hot temperatures, are also poorly understood.

There is a lack of data on the long-term impact of biostimulants on the productivity and health of agroecosystems. The impact on soil microbiota and the environment requires further investigation, especially in the context of sustainable development. The comparative effectiveness of assorted types of biostimulants, as well as their interaction with other agronomic practices, are still understudied. The purpose of this study was to comprehensively assess the effects of biostimulants on the resistance and productivity of peas under water deficit conditions.

MATERIALS AND METHODS

The study was conducted in 2023 at the Podillia Research Centre of the Podillia State University. For the experiment, the pea variety "Gambit" was chosen, which is a *Pisum sativum* L. variety with a growing season of 75-85 days (from May to July). This variety is characterised by stable yields and adaptation to moderate arid conditions, which makes it suitable for assessing the effects of biostimulants. Plants were grown in a controlled greenhouse environment, where the temperature was kept constant at 22-24°C during the day and 18-20°C at night, which corresponds to suitable conditions for pea growth. Three main groups were created for the study, differing in terms of water supply and treatment with biostimulants. The control group included plants that were grown without biostimulant treatment at optimised soil moisture, which was maintained at 70% of the field moisture capacity.

Experimental group 1 involved growing plants under the same conditions of optimised moisture (70% field moisture capacity), but with additional treatment with biostimulants. Experimental group 2 included plants under water deficit conditions with reduced soil moisture to 30% of the field moisture capacity. This group was divided into two subgroups: experimental Subgroup 2.1, where plants were treated with a biostimulant, and experimental Subgroup 2.2, where no biostimulants were used. Such a division helped to analyse the effects of both water deficit and biostimulants on plants under differing moisture content conditions, as well as to compare the results with the control values. The Aminovit biostimulant was used in combination with the Algafit preparation, which contains a complex of amino acids that stimulate metabolic processes in plants, with the ability to improve physiological processes and increase plant resistance to stressful conditions (Table 1). The preparation was applied by spraying the leaves in the phase of active plant growth, starting from the third week after sowing.

***Table 1**. Effect of biostimulants on plants in different conditions*

Group/subgroup	Growing conditions	Preparations	Dosage (ml/l)	Treatment frequency
Control (Group 1)	Optimum moisture content (70% MWC)**	Not applied	–	–
Optimised with biostimulants (Group 2)	Optimum moisture content (70% MWC)**	Aminovit + Algafit	Aminovit (2 ml) + Algafit (3 ml) per 1 litre of water	Spraying of leaves, every 10 days, starting from the 3rd week after sowing
No treatment (Group 2, Subgroup 2.2)	Water deficit (30% MWC)**	Aminovit + Algafit	Aminovit (2.5 ml) + Algafit (3.5 ml) per 1 litre of water	Spraying of leaves, every 7–10 days, starting from the 3rd week after sowing
With treatment with biostimulants (Group 2, Subgroup 2.1)	Water deficit (30% MWC)**	Not applied	–	

***Note:** MWC – maximum water capacity*
***Source:** developed by the authors*

Containers filled with soil substrate with the addition of perlite were used to grow the plants, which provided homogeneous conditions for the development of the root system. The soil moisture level was maintained using an Irritrol Junior Max automated irrigation system (manufacturer: Irritrol Systems), which enabled precise control of the field soil moisture capacity. The temperature in the greenhouse was regulated using a ThermoGrow TG-100 thermostat (manufacturer: ThermoTech). Modern instruments were used to measure physiological parameters. Photosynthetic activity was determined using a LI-6400XT portable gas exchange analyser (manufacturer: LI-COR Biosciences), which measured the intensity of carbon dioxide assimilation. The level of transpiration was determined using a LeafPorometer SC-1 moisture sensor (manufacturer: Decagon Devices), which enabled an accurate assessment of water evaporation through the leaves.

Biochemical parameters were determined by analysing leaf samples. To measure the level of proline, the study employed the method of spectrophotometry with a ninhydrin reaction on a UV-1800 spectrophotometer (manufacturer: Shimadzu). The activity of antioxidant enzymes, such as superoxide dismutase (SOD) and catalase (CAT), was analysed using specific substrates on the same device. These indicators helped to assess how effectively the plants neutralise oxidative stress caused by water deficit. Morphological parameters were assessed at the end of the experiment. The length of the roots, the weight of the root system, and the general condition of the plants were measured. For this, GX-200 digital scales (manufacturer: A&D Company) and Vernier Caliper IP54 calipers (manufacturer: Mitutoyo) were used. The general condition of the plants was determined on a scale from 1 to 10 points, considering visual signs of stress, such as wilting, discolouration of leaves, or stunting. All the data obtained were processed statistically using Statistica 12 software (manufacturer: StatSoft), which helped to analyse the reliability of the findings. This approach helped to draw conclusions about the effectiveness of biostimulants in increasing pea stress resistance and its ability to adapt to adverse water deficit conditions. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS

The results showed that the use of biostimulants positively affected the ability of plants to adapt to stressful conditions and maintain productivity. In Group 1 (control), where moisture conditions stayed optimum, the plants showed stable indicators of the number and weight of beans. However, in Subgroup 2.2 (water deficit without biostimulants), which was experiencing a water deficit, a significant decrease in these indicators was observed. In Subgroup 2.2 (water deficit without biostimulants), a sharp decline in productivity was observed: the number of beans decreased by 46% and the average weight of one bean by 40% compared to control plants. This indicated that plant adaptation mechanisms were insufficient to overcome water stress without additional support. In Subgroup 2.1 (water deficit with biostimulants), the number of beans decreased by only 23% compared to optimum moisture conditions, while the average weight of one bean decreased by 16%. This demonstrates the effectiveness of biostimulants in mitigating the adverse impact of stressful conditions, enabling plants to maintain productivity even under adverse conditions. These findings are explained by the activation of adaptive mechanisms that were enhanced by the biostimulant treatment.

Physiological analyses confirmed the positive effects of biostimulants on plant resistance to stressful conditions (Khalid *et al.*, 2024). In plants of Subgroup 2.1 treated with biostimulants, an increase in the activity of antioxidant enzymes such as SOD and CAT, which play a significant role in reducing oxidative stress, was observed. There was also a 1.5-fold increase in the level of proline compared to Subgroup 2.2, which provided better osmoprotection of cells under stressful conditions. Plants treated with biostimulants maintained stable photosynthetic activity even under water deficit conditions. Unlike plants in Subgroup 2.2 with water deficit, which showed a significant decrease in photosynthetic activity, plants in Subgroup 2.1 treated with biostimulants maintained a more efficient gas exchange, which contributed to the maintenance of growth and development. In the control group, under optimum water conditions, photosynthesis rates stayed stable.

Morphological changes also confirmed the effectiveness of the biostimulants. Plants in Subgroup 2.1 treated with biostimulants had a more developed root system, which contributed to better absorption of moisture from deep soil layers. In contrast, the root system of the control plants from Subgroup 2.2 with water deficit was less developed, which limited their ability to withstand droughts. These findings confirmed the effectiveness of biostimulants in increasing plant stress resistance (Table 2).

***Table 2**. Comparison of plant productivity in control and biostimulant-treated conditions*

Experiment conditions	Plant group	Beans, pcs	Average mass of 1 bean, g	Productivity reduction, %
Optimum moisture content	Control (Group 1)	50	0.35	–
	Optimum with biostimulants (Group 2)	52	0.37	–
Water deficit	No treatment (Group 2, Subgroup 2.2)	27	0.21	46/40
	With biostimulant treatment (Group 2, Subgroup 2.1)	40	0.31	23/16

***Source:** developed by the authors*

Quantitative data also show the benefits of using biostimulants. Water deficit conditions significantly affected the yield of Subgroup 2.2 (water deficit without biostimulant treatment), which was not treated with biostimulants, while the control group (Group 1), which was grown under optimum moisture conditions, showed stable yields. In Group 2, a slight improvement in productivity was recorded compared to the control group: the number of beans increased to 52, while the average weight of one bean increased to 0.37 g. This is evidence of the stimulating effects of biostimulants even under optimum moisture conditions. The data analysis revealed that in Subgroup 2.2 (water deficit without biostimulant treatment), under water deficit conditions, the average yield of control plants was only 60% of the level recorded under optimum moisture conditions. In contrast, in Subgroup 2.1, which received biostimulant treatment, the yield was about 82%, suggesting a significant reduction in productivity losses due to the use of biostimulants. The use of biostimulants reduced yield losses by 25% compared to control plants under stressful conditions, demonstrating the effectiveness of these products in maintaining productivity even under water shortages.

The next stage of the study was to investigate the effects of biostimulants on the physiological parameters of peas. The analysis included measurements of photosynthetic activity, transpiration, antioxidant enzyme activity (SOD and CAT), proline levels, and chlorophyll content. The findings revealed that in Subgroup 2.2, the photosynthetic activity under stressful conditions decreased to 60% of the control level under optimum moisture content conditions, while in Subgroup 2.1, this indicator stayed at 82%. The data indicate that the biostimulants helped the plants to maintain the efficiency of photosynthetic processes necessary to support growth and development (Baltazar *et al*., 2021). The level of transpiration also showed marked differences between the groups. In the control group (Group 1), the level of transpiration was 100%, while in Group 2 (treated) it increased slightly to 102% due to increased water exchange. In the control Subgroup 2.2, transpiration decreased to 50%, indicating a sharp restriction of the water balance of plants under stress. At the same time, in Subgroup 2.1, where biostimulants were used, transpiration was maintained at 75%, ensuring better water exchange and efficient use of moisture.

The activity of antioxidant enzymes SOD and CAT confirmed the protective effect of biostimulants under stressful conditions. In the control (Group 1), the enzyme activity was taken as 100%, while in Group 2 it increased to 110%, indicating stimulation of the antioxidant system. In Subgroup 2.2, the activity of SOD and CAT decreased to 70%, suggesting increased oxidative stress due to moisture deficiency. At the same time, in Subgroup 2.1, the enzyme activity reached 145%, which provided considerable protection of cells from oxidative damage. This information is based on data confirming that enzymes play a vital role in reducing oxidative stress in response to moisture deficit. The level of proline, a significant amino acid for osmoprotection, also revealed substantial changes. In the control (Group 1), this indicator was 1 unit, while in Group 2 – 1.1 units, which confirmed the insignificant effects of biostimulants at optimum moisture content. In Subgroup 2.2, the level of proline increased to 1.5 units, which was the response of plants to water stress. However, in Subgroup 2.1, the proline level reached 2.5 units, which confirmed the activation of adaptive mechanisms due to the use of biostimulants.

Chlorophyll content is a vital indicator of plant resistance to stressful conditions (Cherven *et al*., 2024). In the control (Group 1), this indicator was 100%, while in Group 2 it increased to 104%, which demonstrated the stimulating effects of biostimulants on the photosynthetic apparatus. In Subgroup 2.2, the chlorophyll content decreased to 58%, suggesting the inhibition of photosynthetic processes under stressful conditions. In Subgroup 2.1, where biostimulants were used, the chlorophyll content was maintained at 80%, which confirmed the effectiveness of the preparations in preserving the physiological activity of plants (Ostrowski *et al*., 2020). Maintaining a strong level of chlorophyll was a crucial indicator of plant resistance to drought, as this pigment is a key component of photosynthesis (Table 3).

***Table 3**. Physiological parameters of control and biostimulant-treated plants under different soil moisture conditions*

Indicator	Control group (group 1, optimum moisture content)	Treated group (Group 2, optimum moisture content)	Control Subgroup 2.2 (water deficit)	Treated Subgroup 2.1 (water deficit)
Photosynthetic activity, %	100	105	60	82
Transpiration level, %	100	102	50	75
SOD and CAT activity, %	100	110	70	145
Proline level, relative units	1.0	1.1	1.5	2.5
Chlorophyll content, %	100	104	58	80

***Source:** developed by the authors*

The results of this stage confirmed that biostimulants considerably improve the physiological parameters of plants under water deficit conditions. Plants treated with biostimulants (Subgroup 2.1) maintained greater levels of photosynthesis and transpiration, supported antioxidant protection, and accumulated more osmoprotectors such as proline. This enabled them to withstand stress more effectively and maintain physiological stability. The next stage of the study was to investigate the changes in pea adaptation mechanisms that occurred under the influence of biostimulants in conditions of water deficit. This stage was aimed at understanding how these products affect the internal processes of plants that ensure their resistance to drought, and what physiological and biochemical changes contribute to improved adaptation.

To start with, the study analysed osmotic regulation in plants. This process is one of the key mechanisms that enables plants to maintain water balance even under conditions of limited access to moisture. In control plants that were not treated with biostimulants, a considerable disturbance of osmotic balance was observed, which was manifested in a decrease in cell turgor and wilting of leaves. At the same time, Subgroup 2.1 showed significantly better osmotic regulation. This was achieved due to an increase in the accumulation of osmoprotectants, specifically proline and soluble sugars, which act as osmoregulators, stabilising the water balance in cells. After analysing osmotic regulation, the next step was to study morphological changes in plants. The focus was on the development of the root system, as the roots are the key organ that provides plants with access to water from deep soil layers. Under conditions of water deficit, Subgroup 2.2, which was not treated with biostimulants, experienced a decrease in root length and weight. This limited the ability of plants to effectively absorb moisture from the soil, which substantially affected adaptation to stressful conditions. In the control group with optimum moisture conditions, no such changes were observed. At the same time, in Subgroup 2.1, the root system developed more actively. It was longer and had a greater total weight, which indicated a stimulating effect of biostimulants on root growth even under stressful conditions. These data confirmed that the improvement in water uptake due to biostimulant treatment provided plants with sufficient water to support the basic physiological processes necessary for growth and development (Franzoni *et al.*, 2022).

Additionally, changes in leaf structure were analysed. Plants in Subgroup 2.2, which were exposed to water deficit conditions, showed a decrease in leaf area and density, which is a typical adaptive response to drought. In Subgroup 2.1, which was grown under optimum moisture conditions, no such changes were recorded. The leaves retained a larger area and density, which ensured more efficient absorption of sunlight for photosynthesis. This enabled the plants to maintain a greater level of metabolic activity even in conditions of water deficit, based on the data (Chaski & Petropoulos, 2022). One of the key aspects of the study was to examine changes in the antioxidant defence of plants. During drought, reactive oxygen species accumulate in plant cells, which can cause damage to cell membranes, proteins, and DNA. To neutralise these harmful compounds, plants activate antioxidant mechanisms. In plants, the activity of antioxidant enzymes such as SOD and CAT was insufficient to effectively protect against oxidative stress. This led to extensive damage to cellular structures. In plants treated with biostimulants 2.1, the activity of SOD and CAT increased by 1.5-2 times compared to control plants. This reduced the level of oxidative stress and preserved the integrity of cell membranes.

The next step was to study changes in the content of stress hormones, specifically abscisic acid. In the control plants, the concentration of abscisic acid was considerably higher, indicating a strong response to drought. At the same time, in plants treated with biostimulants, the level of abscisic acid was lower, indicating the ability to better adapt to stress without excessive activation of stress mechanisms. This confirmed the regulatory role of biostimulants in mitigating the adverse effects of drought (Ma *et al.*, 2022). The study ended with an assessment of the general condition of the plants. The Subgroup 2.2 showed signs of severe stress, such as wilting, stunting, and reduced productivity. At the same time, in Subgroup 2.1, these signs were less pronounced, and the general condition stayed stable. This indicated that biostimulants considerably increased plant resistance to drought by activating adaptive mechanisms (Table 4).

***Table 4**. Changes in pea adaptation mechanisms under the influence of biostimulants*

Parameter	Control Subgroup 2.2 (water deficit)	Treated Subgroup 2.1 (water deficit)	Changes in the treated group, %
Level of osmoprotectants	100	170	+70
Root length, cm	15	25	+67
SOD and CAT activity, %	100	200	+100
Abscisic acid level	150	100	-33
General condition of plants (score)	3	8	+166

***Source:** developed by the authors*

The findings of this stage revealed that biostimulants activate various adaptive mechanisms of peas, such as improving osmotic regulation, stimulating the development of the root system, increasing antioxidant protection, and reducing the level of stress hormones. As a result, the plants adapted more effectively to water shortages, maintaining the stability of physiological processes and general condition. This confirmed the high effectiveness of biostimulants in improving plant resistance to drought conditions. The study demonstrated that the use of biostimulants has a comprehensive positive effect on peas under water deficit conditions. The effect of the preparations was manifested in the improvement of physiological, biochemical, and morphological parameters of plants, which played a key role in adaptation to stressful conditions. The findings showed that the biostimulants activated natural plant defence mechanisms, reducing the effects of stress and maintaining productivity.

One of the key mechanisms activated by biostimulants was the regulation of photosynthetic activity. In plants that did not receive biostimulants, water deficit led to a substantial reduction in photosynthesis due to gas exchange restrictions and chloroplast dysfunction. At the same time, in the treated plants, this process stayed stable, with a decrease in activity of only 18% compared to optimum conditions. This helped to save energy for growth and development even under stressful conditions. Transpiration played a significant role in maintaining the water balance. In the control group, plants reduced transpiration by 50% in an attempt to minimise water loss, but this also negatively affected the photosynthesis. In the plants treated with biostimulants, the level of transpiration decreased by only 25%, which enabled them to maintain the water balance and ensure efficient gas exchange.

One of the key findings of the study was an increase in the antioxidant defence of plants under the influence of biostimulants. During drought, reactive oxygen species accumulate in plants, causing damage to cell membranes, proteins, and DNA. In control plants, the activity of antioxidant enzymes such as SOD and CAT was insufficient to protect cells from oxidative stress. In plants treated with biostimulants, the activity of these enzymes doubled, which ensured the protection of cellular structures and reduced the level of oxidative stress. Osmoregulation, which is a vital component of adaptation to water deficit, was also greatly improved in plants treated with biostimulants. These plants significantly increased the level of proline, an osmoprotectant that helps cells store water and maintain the stability of enzymatic processes. In the control group, the level of proline increased by only 50% compared to optimum conditions, while in the treated plants, this indicator increased by 70%.

Morphological changes were also significant. In the control plants, the development of the root system was limited, which reduced their ability to obtain water from deep soil layers. In contrast, in plants treated with the biostimulants, the length of the roots increased by 67%, which ensured access to water even in drought conditions. The leaves of the treated plants also retained a larger area and density, which contributed to more efficient photosynthesis. These changes resulted in maintaining pea productivity even under stressful conditions. In the control group, the number of beans decreased by 46%, while in the treated plants this figure decreased by only 23%. The average weight of beans in the control plants decreased by 40%, while in the treated plants – only by 16%. This showed that biostimulants not only improved plant adaptation to drought but also ensured stable productivity.

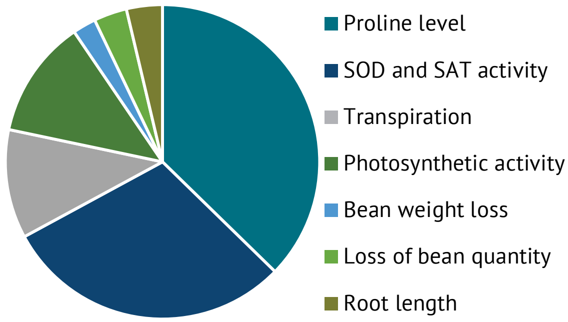

***Figure 1**. Distribution of key physiological and biochemical parameters that influenced the adaptation of peas to stressful conditions after the use of biostimulants*
***Source:** developed by the authors of this study*

The largest contribution belonged to the activity of antioxidant enzymes (SOD and CAT) and proline levels, which are considerably greater than those of the control group. This indicates the significance of these parameters in reducing oxidative stress and maintaining plant water balance (Sattar *et al.*, 2024). Photosynthetic activity and transpiration also account for a considerable share, ensuring the stability of basic physiological processes even under stressful conditions. Root length, although accounting for a smaller share, reflects improvements in morphological characteristics that enable plants to obtain water more efficiently. Losses in the number and weight of beans were the least pronounced, suggesting that the plants treated with biostimulants retain their productivity. This highlights the effectiveness in maintaining vital functions and yields even under water deficit conditions (Jacomassi *et al.*, 2022). The figure demonstrated that biostimulants provide a complex effect by activating interrelated plant adaptive mechanisms.

DISCUSSION

The findings of the study confirmed that the use of biostimulants considerably increases the resistance of peas to water deficit by activating physiological, biochemical, and morphological adaptation mechanisms. Photosynthetic activity, which underlies plant productivity, was substantially reduced in the control group due to gas exchange restrictions. In plants treated with biostimulants, this indicator stayed stable, suggesting the ability to maintain chloroplast function and support the synthesis of organic matter even under stressful conditions. The biostimulants also provided optimum regulation of transpiration, enabling plants to maintain water balance without substantially limiting gas exchange. Control plants that had a sharp decrease in transpiration showed major difficulties in maintaining the required level of photosynthesis, which adversely affected their growth and development.

Biochemical parameters also confirmed the effectiveness of the biostimulants. The high proline levels in the treated plants protected cells from dehydration, maintaining the stability of physiological processes. The activity of antioxidant enzymes such as SOD and CAT was significantly greater in the treated plants, which reduced oxidative stress and prevented damage to cell membranes. Morphological changes, specifically the development of the root system, suggest that the biostimulants stimulated the formation of longer and more massive roots (Burdina & Priss, 2016; Myronycheva *et al.*, 2017). This helped the plants to obtain moisture from deeper soil layers, ensuring a stable water balance (Yeraliyeva *et al.*, 2017). The findings of the study on the impact of biostimulants on pea adaptation mechanisms under water deficit conditions are consistent with and complement the findings of other researchers. However, in many respects, this study has a deeper level of detail, especially in the assessment of physiological, biochemical, and morphological changes. V. Mazur *et al.* (2022) focused on the technological methods of growing peas in the Right-Bank Forest-Steppe of Ukraine. The researchers confirmed the value of maintaining photosynthetic activity to ensure pea yields. They concluded that optimisation of agronomic conditions, specifically soil moisture, is crucial for plant adaptation. The present study complemented these findings by demonstrating that the use of biostimulants further increases photosynthetic activity even under water deficit conditions, which was not detailed in V. Mazur *et al.* was not considered in detail. M.V. Peresunko (2021) studied the influence of technological methods on the grain productivity of peas. The researcher's experiment revealed that the level of productivity substantially depends on the methods of growing and processing crops. At the same time, the study did not analyse biochemical parameters such as proline levels or antioxidant enzyme activity. This study showed that biostimulants affect not only productivity, but also key internal mechanisms that contribute to stress adaptation. M.P. Saltan (2020) analysed the effects of microfertilisers on maize productivity, which is analogous to the present study in the context of the effects of agrotechnology on plant adaptation. The researcher found that fertiliser application reduces yield losses, but the study did not address the mechanisms underlying this adaptation. The present study took a deeper look at the impact of biostimulants, demonstrating that the effectiveness is conditioned by improved antioxidant defence and osmotic regulation.

In their review of unmanned agricultural machinery, B. Khokhlov *et al.* (2023) focused on innovative methods of increasing the productivity of the agricultural sector. The researchers noted that modern technologies, including automated monitoring systems, helped to optimise crop cultivation by precisely controlling environmental parameters such as soil moisture and plant health. This approach is consistent with the current use of automated soil moisture monitoring systems. However, B. Khokhlov *et al.* focused mainly on technical aspects, while the present study complemented this by analysing the biological mechanisms of pea adaptation to water deficit. Specifically, they demonstrated how biostimulants contribute to the preservation of photosynthetic activity, root development, and antioxidant enzyme activity, which was not considered in the researchers' review. S.O. Butenko (2022) analysed the influence of growth regulators with anti-stress effect on the productivity of white mustard in the northeastern Forest-Steppe of Ukraine. The researcher emphasised that the use of such products can substantially reduce yield losses under stressful conditions. The similarity between the present study and S. Butenko's research lies in the investigation of the effects of biological products on plant adaptation to stressful conditions. However, the present study had a wider range of analysis. It not only assessed plant productivity, but also examined internal mechanisms of adaptation, such as increased proline levels, antioxidant enzyme activity, and transpiration regulation. This helped to better understand how biostimulants affect plant resistance to water deficit. S.V. Didichenko and N.V. Telekalo (2020) considered the technological aspects of increasing crop productivity. The researchers emphasised that optimisation of agronomic practices, including the choice of fertilisers and cultivation methods, is crucial for the adaptation of crops to adverse conditions. The findings of these researchers are useful in the context of managing external factors. The present study went beyond general agronomic aspects by detailing the physiological and biochemical mechanisms underlying adaptation. For example, the present study revealed that biostimulants activate plant antioxidant defences by increasing SOD and CAT activity, which was not covered in the researchers' study.

O.O. Tsokalo (2022) focused on the significance of improving cultivation technologies to maintain plant productivity in the face of climate change. The researcher emphasised that adaptation of crop production requires both optimisation of agricultural technologies and introduction of innovative methods. The present findings confirmed the conclusions of O.O. Tsokalo and considerably supplemented them by the analysis of the effects of biostimulants on osmoregulation and antioxidant protection of plants. The data revealed that by increasing the level of proline and CAT and SOD activity, plants can counteract stress more effectively. A.Y. Romanko (2021) investigated the development of soybean productivity depending on the technological methods of cultivation. The researchers emphasised the significance of applying microfertilisers and growth regulators to maintain yields under adverse conditions. The present study is consistent with these findings but extended them by evaluating concrete physiological and biochemical processes that affect plant adaptation to water deficit. For instance, this study demonstrated that biostimulants promote the development of the root system, which is critical for maintaining water balance under stressful conditions.

The study confirmed that the use of biostimulants provides a comprehensive effect on the resistance of peas to water deficit. The uniqueness of the findings lies in the identification of the relationship between the increase in photosynthetic activity, activation of antioxidant defence, optimisation of transpiration and development of the root system. Comparison with other studies demonstrated that the present study expands the existing knowledge by supplementing it with an analysis of physiological and biochemical mechanisms of adaptation. This emphasised the value of biostimulants as an innovative tool for increasing crop productivity under stressful conditions.

CONCLUSIONS

The study conducted a comprehensive analysis of the effects of biostimulants on the physiological, biochemical, and morphological adaptation mechanisms of pea (*Pisum sativum L.*) under water deficit conditions. Particular attention was paid to the assessment of photosynthetic activity, transpiration, antioxidant enzyme activity, osmotic regulators, and morphological changes in plants. The findings provided a comprehensive understanding of how biostimulant treatment contributes to increased crop resistance and productivity under stressful conditions. The present study also confirmed that biostimulants positively affect the plant physiological processes. Specifically, the photosynthetic activity of the treated plants stayed at 82% of optimum conditions even under water deficit, which indicates the stability of chloroplast functioning and carbon dioxide assimilation processes. This helped the plants to maintain the synthesis of organic compounds and meet the energy needs for growth and development. The level of transpiration in plants treated with biostimulants was 75%, indicating effective regulation of water evaporation to maintain water balance.

Biochemical parameters revealed that biostimulants activate adaptive mechanisms at the molecular level. The activity of antioxidant enzymes (SOD and CAT) was greater in the treated plants, which helped to reduce the level of oxidative stress caused by the accumulation of reactive oxygen species. The increased level of proline, which increased to 2.5 relative units, contributed to osmoprotection of cells, reducing their dehydration and maintaining turgor. Morphological studies showed that biostimulants considerably improve the development of the root system. The length and weight of the roots of plants treated with biostimulants were greater, which allowed for better absorption of moisture from deep soil layers. This ensured a stable water supply even in conditions of water shortage, which was not achieved in the control subgroup.

Productivity was also significantly greater in plants treated with biostimulants. Losses in the number and weight of beans under stressful conditions were considerably lower than in the control subgroup. The treatment with biostimulants reduced the yield decline, while maintaining stability even under unfavourable conditions. This confirmed that biostimulants not only preserve the vital activity of the crop but also contributed to the stable formation of the yield. The study emphasised the value of an integrated approach that factors in the physiological, biochemical, and morphological aspects of biostimulants. The findings demonstrated that the use of biostimulants has great potential to increase crop resilience to climate change and ensure stable productivity.

At the same time, the experiments were conducted under controlled conditions, which limited the extrapolation of the findings to field conditions with multiple stressors. Further research should focus on long-term field experiments, considering the interaction of biostimulants with other agricultural technologies to create integrated solutions in arid regions.

ACKNOWLEDGEMENTS

None.

CONFLICT OF INTEREST

None.

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Вплив біостимуляторів на фізіологічні процеси, продуктивність та якість врожаю гороху в умовах сучасного землеробства

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Анотація. Метою дослідження було вивчення впливу біостимуляторів на підвищення адаптаційних механізмів гороху (*Pisum sativum* L.) в умовах дефіциту води, з акцентом на оптимізацію фізіологічних функцій, біохімічних процесів та морфологічного розвитку рослин. Експеримент проводився у контрольованих умовах, які дозволяли точно моделювати вплив водного стресу. У рамках дослідження використовувалися комплексні методи оцінки, що включали фізіологічні показники (фотосинтетична активність, транспірація), біохімічні маркери (активність антиоксидантних ферментів, рівень проліну) та морфологічні параметри (довжина і маса кореневої системи).Результати підтвердили, що обробка біостимуляторами значно підвищувала адаптаційний потенціал рослин. Фотосинтетична активність у рослин, які отримували обробку, становила 82 %, що суттєво перевищувало показник контрольної групи, де цей рівень досягав лише 60 %. Транспірація в оброблених рослин залишалася стабільною, забезпечуючи оптимальний водний баланс навіть за умов стресу. Біохімічний аналіз показав, що активність супероксиддисмутази і каталази у рослин, оброблених біостимуляторами, зросла на 145 % порівняно з контрольними, що сприяло значному зниженню оксидативного стресу. Рівень проліну, як ключового осмотичного регулятора, також був значно вищим у оброблених рослин, що підтримувало стабільність клітинного водного балансу. Морфологічні дослідження виявили, що рослини, оброблені біостимуляторами, мали розвиненішу кореневу систему: довжина коренів була більшою на 10 см, а маса перевищувала контрольні показники. Це дозволяло рослинам використовувати вологу з глибших шарів ґрунту, що покращувало їхню стійкість до посухи. У підсумку втрати врожайності у рослин, які отримували обробку, були вдвічі меншими, ніж у контрольній групі. Отримані результати підкреслюють ефективність використання біостимуляторів для підвищення стійкості гороху до водного дефіциту та збереження продуктивності. Це робить запропонований підхід перспективним для впровадження в агротехнології, особливо у посушливих регіонах, де дефіцит вологи є основним обмежувальним фактором для сільськогосподарських культур

Ключові слова: адаптація рослин; абіотичні фактори; стресостійкість; транспірація; водний баланс