



Regulation of morphometric parameters of winter barley (*Hordeum vulgare* L.) using graphene oxide under water stress

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Abstract. The problem of food security due to extreme climate change is critical in Europe and globally, and its solution is one of the sustainable development goals, as the amount of precipitation decreases annually, and the average annual temperature increases, which leads to the spread of droughts, lengthening rainless periods, and complicates the cultivation of crops. The purpose of the study was to investigate the effect of structured graphene oxide nanoparticles during pre-sowing treatment of winter barley seeds (*Hordeum vulgare* L.) varieties 'Dostoinyi' of morphometric parameters of plants in conditions of water deficiency. Chemical, physical, and physiological methods were applied. The effect of graphene oxide at concentrations of 5, 10, 20, and 50 micrograms/ml on the morphometric parameters of winter barley was studied 17 days after seed treatment under conditions of regular watering and water stress. No phytotoxic effect of graphene oxide on barley seedlings with regular watering was detected. Pre-sowing treatment of seeds with graphene oxide at a concentration of 5 micrograms/ml showed a maximum increase in root length (by 35%) and plant height (by 23%) with water deficiency compared to the control. At other concentrations studied, plant growth was also stimulated, but the effect was less pronounced. The weight of plants at optimal concentrations of graphene oxide increased slightly, and with water deficiency, the increase was minimal. Graphene oxide effectively improved the development

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of the barley root system in conditions of water scarcity, which is important for plant adaptation to drought. The practical significance of the study lies in the fact that the results obtained substantiate the feasibility of using nanoparticles as an effective agricultural technology to increase the stress resistance of agricultural crops to water scarcity

Keywords: grain crops; drought resistance; innovative agricultural technologies; nanomaterials; pre-sowing treatment

INTRODUCTION

Rapid climate change is a significant problem in contemporary agricultural production. Every year, the amount of precipitation decreases, the average annual temperature increases, and there is a sharp unevenness alternating dry and rainy periods, which leads to prolonged droughts and, accordingly, complicates the cultivation of agricultural crops. The water regime plays an extremely important role in the functioning and vital activity of all living organisms, and in crop production it is a key factor in yield – it regulates all the necessary physiological and biochemical functions, in particular, the transport of nutrients, photosynthesis, and respiration, etc.

Research by A. Filipovic (2020) on the dynamics of water in the soil-plant-air system showed the extreme complexity of this process and its dependence on a number of factors. The researcher found out the key mechanisms that allow plants to adapt to water stress, including through the increased development of the root system, which is an adaptive defence mechanism in conditions of lack of moisture. Experimental results show that even minor changes in the amount of soil moisture have a significant impact on transpiration and overall plant productivity. The study by T. Kompas *et al.* (2024) showed that water-deficient stress is the main cause of reduced vital activity and crop yields, since with a lack of moisture, photosynthetic, respiratory, and metabolic processes are disrupted, leading to plant death and crop losses. According to A. Fathi *et al.* (2024), water deficiency negatively affects plant growth and development, resulting in inhibited DNA synthesis, disrupted cell division, and stretching phases. Consequently, water stress significantly affects agroecosystems and causes risks in shaping global food security not only in Ukraine and Europe, but also in the world as a whole.

Ukraine, despite socio-political conditions and military operations on its territory, remains

one of the leading grain exporters in the world. That is why the issue of stable agricultural production is of strategic importance both for the national economy and for the state's economy to achieve Sustainable Development Goal 2 (Goal 2 – overcoming hunger, achieving food security, improving nutrition, and promoting sustainable agricultural development). However, contemporary environmental challenges, such as increasing climate risks, reducing natural soil fertility, including due to pollution due to fighting, frequent and prolonged droughts, reducing acreage due to fighting, make it difficult for farmers to obtain high yields and significantly increase the risks of losses.

A.A. Nagdalian *et al.* (2023) noted that common barley (*Hordeum vulgare* L.) is one of the most important grain crops with a wide range of uses: from the food industry to the feed base. It is characterised by adaptability to different climatic conditions, resistance to diseases and the ability to form a crop even with a lack of moisture. However, even this crop suffers significant yield losses in conditions of water scarcity. It is relevant to find innovative agrotechnological approaches to regulating stress resistance mechanisms in agricultural crops during prolonged droughts to increase the quantity and quality of plant raw materials. Research by S.V. Prylutska *et al.* (2024) showed the prospects of using structured carbon nanoparticles in this area, which, due to their unique physicochemical and biological properties, in particular, nanoscale and hydrophobicity, can penetrate through biological membranes into cells, transport nutrients, serve as a source of bioorganic substances, and have antibacterial, antiviral, fungicidal, and insecticidal effects.

Y. Yang *et al.* (2022) proved that graphene oxide (GO) is a two-dimensional nanomaterial consisting of carbon atoms organised in a hexagonal grid, on the surface of which there are numerous oxygen-containing functional groups (hydroxyl,

carboxyl, epoxy). The presence of these groups in the GO molecule provides high hydrophilicity, which is manifested in the ability to retain water in the soil, dispersion in water, forms a significant specific surface area and the ability to chemical modification. These properties interact effectively with plant cells. The findings of J. Shoham (2020) proved the positive effect and biological activity of graphene oxide on the growth, development, formation of the reaction to oxidative stress and water imbalance of plants. It was also important to note that nanomaterials contribute to the long-term storage of fertilisers in the soil, respectively, they provide plants with the necessary nutrients for a significant period of time. This approach allows reducing the load on soil ecosystems and the amount of fertilisers used in the long term, minimising contamination of the pedosphere with nutrients. According to L. Zhao *et al.* (2022a), graphene oxide does not accumulate in plant tissues during prolonged use and application to the soil, which eliminates the risks of nanoparticle toxicity and environmental stress. However, questions about long-term field trials, the effect of GO nanoparticles on the soil microbiome, and the economic feasibility of their use remain relevant and require comprehensive further research. In addition, B. Anegebe *et al.* (2024) showed that graphene oxide, due to the unique structural and surface characteristics of the molecule, in particular, large specific surface area, porosity, chemical and mechanical resistance, catalytic activity, can exhibit high efficiency in extracting and removing various environmental pollutants, in particular, pesticides and pharmaceuticals, etc.

Given the urgency of the problem of water stress and the prospects of using nanotechnologies to increase plant resistance to adverse conditions, there is a need to study the effectiveness of using graphene oxide in agricultural production. The purpose of the study was to investigate the effect of pre-sowing treatment of ordinary barley seeds with structured graphene oxide nanoparticles on the morphometric parameters of plants under water deficiency conditions.

MATERIALS AND METHODS

The study was conducted during April – June 2024 at the educational and scientific laboratory

“Biochemistry and phytobiotechnology” of the Department of Physiology, Plant Biochemistry and Bioenergy of the National University of Life and Environmental Sciences of Ukraine. The object of research were the certified seeds of winter barley (*Hordeum vulgare* L.) of the cold-and drought-resistant variety ‘Dostoynyi’, bred by the breeding and genetic Institute of the National Academy of Agrarian Sciences of Ukraine in 2006. The variety was characterised by high productivity, yield, and resistance to powdery mildew, black and blister smut. Winter barley remains a key agricultural crop in Europe, as it is characterised by a higher yield compared to spring barley, as it optimally uses moisture during the seasonal period.

Synthesis and characterisation of structured graphene oxide nanoparticles. Samples of water-soluble dispersed graphene oxide (GO) nanoparticles at an initial concentration of 4 mg/mL were provided by Graphenea S.A. (San Sebastian, Spain). Highly stable aqueous solutions of GO nanoparticles were used in the work. The authors confirmed the structural organisation and stability of the samples using high-resolution microscopy and dynamic light scattering. The studies used an aqueous solution of GO in the concentration range: 5, 10, 20, and 50 mcg/ml, as these are pilot studies of the phytotoxic properties of nanoparticles.

Experimental conditions. Pre-sowing treatment of barley seeds was carried out in two stages: sterilisation and priming (Fig. 1). To do this, the seeds were soaked sequentially: 1) in a 3% solution of H_2O_2 for 25 minutes, after which they were washed three times with distilled water; 2) in a solution of H_3BO_3 (0.6 g/l) for 15 minutes, then washed again three times with distilled water; 3) in GO solution at the test concentrations (5, 10, 20, and 50 mcg/ml) for 5 hours. Barley seeds in the control group (without GO treatment) were soaked only in distilled water.

The treated barley seeds were planted in a universal soil mixture produced by Florida (Ukraine) consisting of turf soil, high-moor peat, low-moor peat, river sand, mineral fertilisers (N, P, K), microelements (Fe, Zn, B, Cu, Mo, Mn), pH 5.5-7.5, in 1-litre containers. Each control and experimental samples contained 10 seeds. The seeds were sprouted at a temperature of +20°C and 15/9 photoperiod for 16 days.

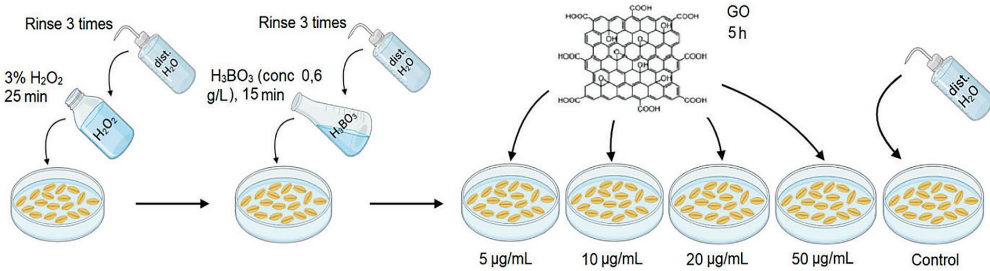


Figure 1. Scheme of seed treatment for winter barley *Hordeum vulgare* L

Source: created by the authors

The experiments included the following groups:

A) regular watering (5 variants): 1) control (without GO treatment) and experimental groups of plants treated: 2) 5 mcg/ml GO, 3) 10 mcg/ml GO, 4) 20 mcg/ml GO, 5) 50 mcg/ml GO.

B) water scarcity (5 variants): 1) control (without GO treatment) and experimental groups of plants treated: 2) 5 mcg/ml GO, 3) 10 mcg/ml GO, 4) 20 mcg/ml GO, 5) 50 mcg/ml GO.

Measurements were performed for at least three repetitions of each experiment variant.

Simulation of a drought under laboratory conditions. During the experiment, the drought for barley plants was simulated by the Tumanov wilting method, and the spraying of plants was stopped on day 2 after seed germination (Pykalo et al., 2020). Watering of the samples was resumed 1 day before the end of the experiment. Spraying of control samples (without drought modelling) was carried out regularly – every second day. This method and duration were used in the work to model water scarcity, since it is universal for cereals, which was also confirmed by the reaction of barley due to the intensification of root length.

Morphological indicators in control (without processing GO) and experimental (processed GO) variants of plants with regular watering and water deficiency were evaluated on day 17 after seed germination, namely, in the vegetative phase of four leaf formation. Selection and preparation of plant material and determination of morphometric parameters (plant height, shoot and root length, plant weight) were carried out according to generally accepted methods. For each variant of the experiment, a minimum of 10 plants were selected in each sample, with at least three biological repeats per variant, which corresponds to the

approaches for evaluating seedlings in contemporary studies on morphometry of barley and other crops (Mahmood et al., 2022). To do this, the plants were carefully separated from the soil mixture by holding the root zone; the remaining substrate was removed by light washing in a tray with distilled water and short drying on filter paper until there was no free moisture on the surface. The height of the plant was determined as the distance from the root neck to the top of the highest leaf/shoot in a straightened but not stretched state; the length of the shoot – from the root neck to the top of the main shoot; the length of the root – from the root neck to the top of the longest root; all measurements were made with a ruler with an accuracy of 1 mm. The fresh weight of plants was determined immediately after linear measurements on analytical scales with an accuracy of 0.1 mg. Measurements were performed at the same time of day and under the same laboratory conditions to minimise the effect of daily fluctuations in turgor and evaporation on morphometric parameters (Ergun et al., 2024).

Statistical processing of the study results were performed using ANOVA analysis of variance and Microsoft Excel 2010 and GraphPad Prism 7 software, the results were considered significant at the values $P < 0.05$. Experimental plant studies were in line with institutional, national, and international guidelines. The authors adhered to the standards of the Convention on Biological Diversity (1992).

RESULTS AND DISCUSSION

Water-deficient stress significantly affects the state of agroecosystems and the development of global food security in the world. Solving these complex agricultural production problems requires using the latest biotechnological approaches.

Nanoparticles, in particular graphene oxide, can be used as regulators of crop resistance to water stress in agricultural technologies. Its surface is modified with oxygen-containing functional groups, which provides high hydrophilicity and the ability to retain water in the soil and interact with plant cells. Nanoparticles mostly do not exhibit phytotoxic effects even at high concentrations, and optimal concentrations have a positive effect on the morphological and physiological parameters of plants (Zhao *et al.*, 2022a).

The study was conducted on winter barley plants (*Hordeum vulgare* L.) of the 'Dostoynyi' variety, which is characterised as a high-yielding and resistant to extreme environmental conditions and diseases variety. A preliminary study of the effect of graphene oxide nanoparticles on the morphometric parameters of plants of various species showed that at optimal concentrations of carbon nanomaterials (5-100 mcg/ml for seed treatment or 20-50 mg/l for foliar application), root growth was stimulated and aboveground mass was increased, yield and product quality were increased (Zhang *et al.*, 2021; Yang *et al.*, 2022; Prylutska *et al.*, 2024). Both growth regulators and graphene oxide affect plant growth depending on the dosage and concentration of the substance, so it is important to determine the optimal concentrations to achieve maximum agronomic effect. On day 17 of germination of common barley seeds treated in various concentrations, which were grown in artificial drought conditions, the main morphometric parameters were measured (Fig. 2).

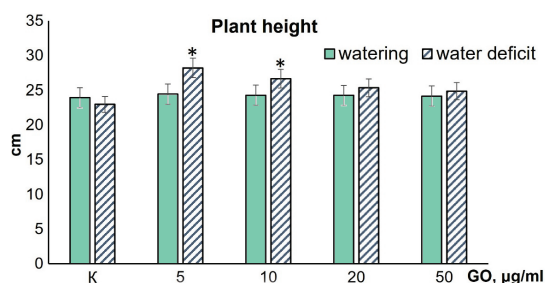


Figure 2. Plant height (cm) of winter barley (*Hordeum vulgare* L.) of the 'Dostoynyi' variety on day 17 after germination of the treated seeds with graphene oxide under conditions of regular watering and water deficiency ($M \pm m$, $n = 10$)
Note: * $p < 0.05$ compared to the control (untreated plants)
Source: created by the authors

Under conditions of regular irrigation, there were no statistically significant differences in the total length of barley plants (Fig. 2). But in the conditions of moisture deficiency in the GO seed treatment option of 5 mcg/ml, an increase in the total length was determined by 23%, and at a concentration of 10 mcg/ml – by 18%. In the remaining variants, no statistically significant length gain was observed. Higher concentrations also stimulated plant growth, but these indicators were insignificant and did not significantly differ from the control values.

A similar trend was observed in the increase in the stem length of barley plants (Fig. 3). In the case of using graphene oxide nanoparticles and regular irrigation of plants, a slight increase in stems was noted. The total length increased by 2-8% compared to the control, which is statistically insignificant. Moreover, even a small increase was dose-dependent – the greatest increase in stem length was observed at the GO concentration of 5 micrograms/ml, followed by a decrease in the indicator with an increase in the concentration of nanoparticles in solution.

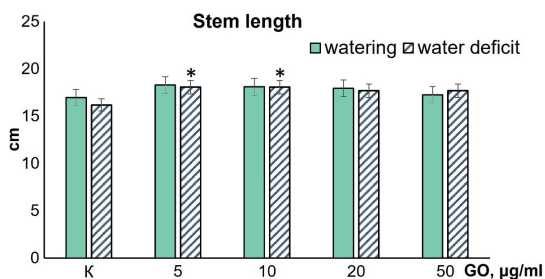


Figure 3. Plant stem length (cm) of winter barley (*Hordeum vulgare* L.) of the 'Dostoynyi' variety on day 17 after germination of the treated seeds with graphene oxide under conditions of regular watering and water deficiency ($M \pm m$, $n = 10$)
Note: * $p < 0.05$ compared to the control (untreated plants)
Source: created by the authors

Under drought simulation conditions, a pronounced effect of graphene oxide nanoparticles at concentrations of 5 and 10 micrograms/ml was observed – the stem length increased statistically significantly by 11-12% (Fig. 3). At higher concentrations (20 and 50 micrograms/ml of GO), the length increase was 9% compared to control plants. The effect of structured nanoparticles on seeds before sowing helps to better tolerate

adverse conditions, including moisture deficiency, and promotes active growth of the aboveground part of plants. The dry period causes oxidative stress in the plant body, which, in turn, leads to the development of free radicals that damage cells and lead to plant death. Probably, nanoparticles contribute to the activation of the antioxidant system of the plant body, neutralising the resulting free radicals, allowing the plant to better tolerate stressful conditions and maintain vitality during the dry period. Thus, pre-sowing seed treatment contributes to the formation of stress resistance to drought and ensures the development of the stem part of the plant.

The development of the root mass of plants is the key to active growth and development of plants as a whole, but it is the root system that first of all experiences a lack of moisture and reacts to drought by reducing water exchange between plant parts. Therefore, the root length indicator is key in the development of plant resistance to arid conditions. In the experiment, under normal wetting conditions, there was no significant difference in the root length of the barley plant root system after treatment with GO nanoparticles (Fig. 4).

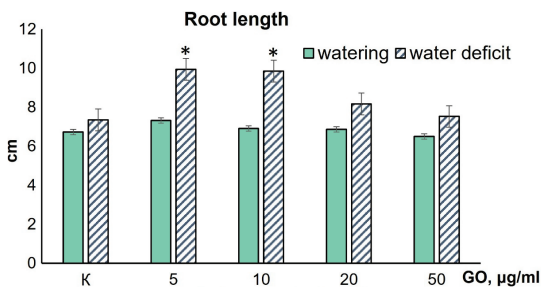


Figure 4. Plant root length (cm) of winter barley (*Hordeum vulgare* L.) of the 'Dostoynyi' variety on day 17 after germination of the treated seeds with graphene oxide under conditions of regular watering and water deficiency ($M \pm m$, $n = 10$)
Note: * $p < 0.05$ compared to the control (untreated plants)
Source: created by the authors

Figure 4 shows that under water stress, plants treated with graphene oxide at concentrations of 5 mcg/ml and 10 mcg/ml showed a significant increase in root length. These values are statistically significant compared to the control and amounted to 35% and 34%, respectively. Increases in graphene oxide concentrations did not

significantly affect barley root growth, but were 2% (50 mcg/ml) and 10% (20 mcg/ml) higher than controls. A well-developed root system penetrates deeper layers of the soil, where capillary moisture is stored, which significantly improves the absorption of water and nutrients during the dry period. Thus, it can be argued that nanoparticles promote more intensive growth and development of the root system, have a positive effect on the development of stress resistance of barley plants to drought, ensuring the growth of the root system and, accordingly, providing a better water balance between the aboveground and underground parts of plants. A general indicator of plant stress resistance under extreme conditions, in particular the onset of dry periods during the growing season, is the vegetative mass of plants. According to this indicator, there are no statistically significant changes in common barley compared to the control both under normal conditions and under simulated drought conditions (Fig. 5).

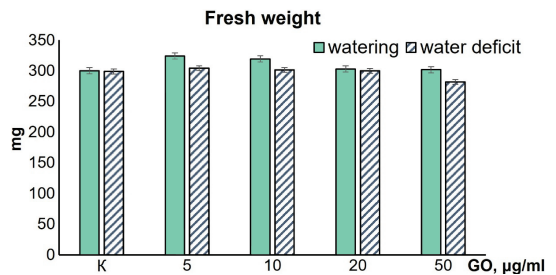


Figure 5. Fresh weight of plants (mg) of winter barley (*Hordeum vulgare* L.) of the 'Dostoynyi' variety on day 17 after germination of the treated seeds with graphene oxide under conditions of regular watering and water deficiency ($M \pm m$, $n = 10$)
Note: * $p < 0.05$ compared to the control (untreated plants)
Source: created by the authors

Figure 5 shows that under irrigation conditions, the increase in biomass of plants treated with graphene oxide at concentrations of 5 mcg/ml and 10 mcg/ml showed an 8 and 6% higher indicator compared to the control, while under conditions of moisture deficiency, this indicator increased only by 2 and 1%, which is a statistically insignificant value. Consequently, with water deficiency in plants treated with graphene oxide, a concentration-dependent effect on the main

morphometric parameters was observed. When exposed to 5 micrograms/ml of graphene oxide, the length of the plant, stem, and root was 23%, 12%, and 35% longer, respectively, compared to untreated plants. And when exposed to 10 mcg/ml of graphene oxide, the morphometric values of plant, stem, and root length were also higher compared to untreated plants by 18%, 11%, and 34%, respectively. At high concentrations (20 and 50 mcg/ml), graphene oxide did not affect the studied parameters.

Barley is the second most common grain crop in the world, widely used as raw materials for the food industry, kvass and brewing, production of animal feed (mixed feed), used in technical areas (biofuel production) and cosmetology. The study by A. Yiğit & F.-M. Chmielewski (2024) pointed out the urgent need to find ways to develop resistance to adverse factors in this crop, since further climate changes will lead to a significant decrease in its yield, which will affect a number of areas of agro- and food production. Thus, it can be argued that under water stress, graphene oxide nanoparticles at concentrations of 5 mcg/ml and 10 mcg/ml showed a significant stimulating effect on plant growth and the formation of their vegetative parts. Increasing the root mass by increasing the length of the roots probably allows plants to use soil moisture to maintain the main processes of vital activity, ensure the growth of aboveground parts of plants, and withstand the dry period without losing biomass.

At elevated concentrations of graphene oxide, no phytotoxic effect on plants was observed in the conducted experiments, namely, changes in the studied morphometric parameters. The absence of phytotoxic effects in the studied range of graphene oxide concentrations is consistent with studies by other researchers. According to Y. Yang *et al.* (2022), graphene oxide at a concentration of 0.2 mg/mL stimulated seed germination of *Festuca arundinacea*, and at a concentration of 50 mg/mL – seed germination of *Spinacia oleracea* and *Allium cepa*, growth of the aboveground and underground parts of *Zea mays*. A. Buziashvili *et al.* (2024) showed that a concentration of 25 mg/mL accelerated germination and growth of *Solanum lycopersicum*. These data fully coincide with the results obtained in the experiment, which confirms the positive effect of graphene oxide

nanoparticles on the growth processes during pre-sowing seed treatment. The absence of phytotoxicity at high concentrations is a direct consequence of the fact that increased concentrations of GO (more than 25 mg/mL) did not show a stimulating effect, but there was no negative effect on plant growth and development. In large quantities in solutions, nanoparticles can aggregate, forming micro- and macroscopic clusters of substances, the size of which does not allow them to enter plant cells and enter into metabolic processes. Thus, a significant number of nanoparticles remain in the soil or settle on the surface of the roots, unable to interact with intracellular structures and influence vital physiological and biochemical processes.

There is evidence of the negative effects of graphene oxide on plants. Research by S. Zhao *et al.* (2023) showed that seed treatment with high concentrations of graphene nanoparticles caused growth inhibition, changes in the anatomical structure of roots, and reduced nutrient uptake in alfalfa (*Medicago sativa* L.), and research by S. Zhao *et al.* (2022b) showed a decrease in the biomass growth of white clover shoots (*Trifolium repens* L.). The substance itself is not phytotoxic, but it can cause negative effects due to the obstruction of access of nutrients and soil moisture to plants. GO agglomerates formed at high concentrations settle on the roots, disrupting normal metabolic processes in the plant. That is why the direction of application of nanoparticles in agrobiotechnologies is promising and requires further detailed and comprehensive research.

In addition, there are a number of literature data on other areas and mechanisms of the influence of graphene oxide on the physiological and agrotechnical parameters of plants. According to M.T. Miranda *et al.* (2020), one of the protective responses in water scarcity and drought is osmotic adaptation of plants, in which the concentration of organic substances, in particular glucose, in roots and leaves increases, and root growth is accelerated compared to shoots. L. Zhao *et al.* (2022a) showed that graphene oxide promotes soybean growth (*Glycine max* L.) without phytotoxic effects and prevented the negative effects of drought on plants. In soybean plants treated with graphene oxide at a concentration of 100 mcg/ml compared to untreated plants, the water content in stems and leaves increased by 127 and 128%, respectively,

the root parameters (total length, surface area, diameter and volume) increased by 33, 38, 34 and 35%, the activity of antioxidant enzymes such as superoxide dismutase, catalase, peroxidase, and ascorbate peroxidase increased by 29, 57, 28 and 66%, the levels of jasmonic, salicylic, and abscisic hormones increased by 32, 34, and 67%, and four drought-related genes were expressed: *gmp5cs*, *gmgols*, *gmdreb1*, and *gmnccd1*. The study showed that graphene oxide directly increased plant defence enzymes, hormone content, and expression of drought-related genes, thereby improving soybean resistance to the negative effects of drought.

The study by Y. Zhang *et al.* (2024) showed that after processing buckwheat (*Fagopyrum tataricum*) with graphene oxide in the concentration range of 25-200 mg/l increased its yield, increased the content of nutrients in the soil of the rhizosphere, growth and activity of roots, the content of photosynthetic pigments, the activity of antioxidant enzymes, the content of auxin. The action of graphene oxide in soybean seedlings increased the content of proline, soluble sugars and other osmotic substances, which contributes to the preservation of cell turgor and resistance to drought (Zhao *et al.*, 2022a). Independent research by L. Zhao *et al.* (2022a) and A.A. Nagdalian *et al.* (2023) showed that after treatment of barley and soybean seeds with silicon nanoparticles, the root length increased by 33-45%, the plant height by 19-22%, and the seedling weight by 10-15% compared to the control under water deficiency conditions. Such data are quite consistent with the results obtained for winter barley varieties 'Dostoynyi', which allows assuming the constancy of the effect of nanoparticles on physiological processes in plants of different species.

N.E. Mahmoud & R.M. Abdelhameed (2021) showed that corn and millet were also treated with graphene nanoparticles to improve morphometric and biochemical parameters, and crop yields increased even on saline soils. T. Lopes *et al.* (2021) proved that graphene oxide and other carbon nanomaterials effectively regulate drought-induced oxidative stress in plants, stimulating root system development and improving morphometric parameters (root length, plant height, biomass). The study by S. Park *et al.* (2020) noted that the use of GO effectively increases the yield and resistance of barley and other crops to water scarcity,

which is particularly relevant in the context of climate change. Moreover, exceeding the optimal doses of graphene oxide can cause growth inhibition, increased oxidative stress, and membrane damage, which indicates the need for clear control of compound concentrations. It is assumed that one of the possible mechanisms of protective action is the ability of nanoparticles to penetrate the seed shell, violate its integrity, which, in turn, facilitates the absorption of water molecules and, as a result, accelerates the germination of plants. In addition, due to oxygen-containing functional groups, graphene oxide retains water, and hydrophobic sites sp^2 -structures promote the transfer of moisture to the seeds, stimulating the germination process of plants.

Considering the numerous positive results of the study of the influence of graphene oxide nanoparticles on the growth and biochemical processes of important agricultural crops, and the findings of researchers, it can be argued that the use of a solution of graphene oxide nanoparticles for pre-sowing treatment of seed material is an evidence-based effective way to increase plant yield, increase the level of their resistance to abiotic stresses, including water deficiency, which is a contemporary challenge of agricultural production in Ukraine.

CONCLUSIONS

Morphometric parameters of winter barley of the 'Dostoynyi' variety after priming seeds with graphene oxide in the concentration range of 5-50 mcg/ml under conditions of regular watering and water stress were studied on day 17 of plant vegetation. There was no negative effect of graphene oxide on barley plants both under conditions of regular watering and water deficiency. Under the influence of drought, there was an increase in the length of the root of plants by 9%. In barley plants sprouted under water stress and pre-treated with graphene oxide, an increase in the studied morphometric parameters was observed. The concentration-dependent effect of nanoparticles on plant growth and development was revealed. At optimally stimulating concentrations of graphene oxide of 5 and 10 mcg/ml, an increase in plant height by 23% and 18%, stem length by 12% and 11%, root length by 35% and 34%, respectively, was observed in relation to plants untreated with nanoparticles

and sprouted under drought conditions. While at higher graphene oxide concentrations of 20 and 50 mcg/ml, the morphometric parameters corresponded to the control values of plants both under conditions of regular watering and water deficiency. The increase in biomass under the influence of nanoparticles was statistically insignificant.

The revealed stimulating effect of graphene oxide on common winter barley plants in arid conditions allows, based on the results obtained, considering nanoparticles as an innovative agricultural technology for adapting this grain crop to moisture deficiency and viewing nanoparticles as highly effective means of maintaining and preserving plant yield. The results obtained indicate the absence of phytotoxic effects of structured graphene oxide nanoparticles and, accordingly, their safety in agricultural production to increase the stress resistance of plants to water stress and long dry periods. However, it is important to

elucidate the intracellular and biochemical mechanisms of plant resistance and establish the nature of adaptive responses to adverse growing conditions using structured nanomaterials, which requires further basic research.

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CONFLICT OF INTEREST

None.

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Регуляція морфометричних параметрів ячменю озимого (*Hordeum vulgare* L.) оксидом графену за водного стресу

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Анотація. Проблема продовольчої безпеки за екстремальних кліматичних змін є критичною у Європі і світі в цілому, а її вирішення є однією з цілей сталого розвитку, оскільки кількість опадів щорічно зменшується, а середньорічна температура зростає, що призводить до поширення посух, подовження бездошових періодів та ускладнює вирощування сільськогосподарських культур. Метою роботи було дослідити вплив структурованих наночастинок оксиду графену при передпосівній обробці насіння озимого ячменю (*Hordeum vulgare* L.) сорту 'Достойний' на морфометричні показники рослин за умов водного дефіциту. У роботі було використано хімічні, фізичні та фізіологічні методи. Вплив оксиду графену у концентраціях 5, 10, 20 і 50 мкг/мл на морфометричні показники озимого ячменю вивчали через 17 діб після обробки насіння за умов регулярного поливу та водного стресу. Виявлено відсутність фітотоксичної дії оксиду графену на проростки ячменю при регулярному поливі. За передпосівної обробки насіння оксидом графену у концентрації 5 мкг/мл спостерігалось максимальне збільшення довжини коренів (на 35 %) та висоти рослини (на 23 %) за водного дефіциту порівняно з контролем. За інших досліджуваних концентрацій також спостерігали стимулювання росту рослин, проте ефект був менш вираженим. Маса рослин за оптимальних концентрацій оксиду графену зростала незначно, а за водного дефіциту приріст був мінімальним. Оксид графену ефективно покращував розвиток кореневої системи ячменю за умов водного дефіциту, що є важливим в адаптації рослин до посухи. Практичне значення дослідження полягає в тому, що отримані результати обґрунтовують доцільність використання наночастинок як ефективної агротехнології для підвищення стресостійкості сільськогосподарських культур до водного дефіциту

Ключові слова: зернові культури; посухостійкість; інноваційні агротехнології; наноматеріали; передпосівна обробка