Chapter 24

CARBON NANOMATERIALS AS REGULATORS OF STRESS RESISTANCE IN PLANTS

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INTRODUCTION

Global climate changes, soil degradation, environmental pollution by xenobiotics, infectious plant diseases are challenges facing the agricultural industry, which determine the need for its modification using the latest farming methods to ensure food security[1, 2].

Territories, which until recently were in a temperate climate zone and were used for growing traditional crops, are affected by extreme conditions, such as salinization, drought, changes in soil acidity, abnormal air temperature, the effect of toxic substances, which causes a decrease in yield and a decrease in its quality[3, 4].

Increasing the stress resistance of cultivated plants is one of the ways to ensure their stable productivity. Currently, various new means and methods are used for this purpose, including modern agricultural technologies, maintenance of phytohormonal balance in critical phases of plant development, cultivation of resistant varieties and lines of plants created by

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[1] Raawtani D., Gupta G., Khatri N., Rao P. K., Hussain C. M. Environmental damages due to war in Ukraine: A perspective. *Science of The Total Environment*. 2022. Vol. 850. DOI: 10.1016/j.scitotenv.2022.157932

[2] Lobell D. B., Gourdji S. M. The Influence of Climate Change on Global Crop Productivity. *Plant Physiology*. 2012. Vol. 160, № 4. P. 1686–1697. DOI: 10.1104/pp.112.208298

[3] Lobell D. B., Schlenker W., Costa-Roberts J. Climate trends and global crop production since 1980. *Science*. 2011. Vol. 333. P. 616–620. DOI: 10.1126/science.1204531

[4] Hatfield J. L., Boote K. J., Kimball B. A., Ziska L. H., Izaurralde R. C., Ort D., Thomson A. M., Wolfe D. Climate impacts on agriculture: Implications for crop production. *Agron J*. 2011. Vol. 103: 351–370. doi:10.2134/agronj2010.0303

traditional selection and genetic engineering, chemical protection agents, nanofertilizers, etc.[5, 6, 7, 8].

At the same time, the use of these approaches is not always justified, as the environmental risks caused by soil, air, water and food raw materials pollutions, the spread and consumption of GM plants, which create potential risks for the end consumer, are ignored.

The development of the agricultural industry at the current stage requires the use of ecological and safe means that would ensure the growth of plant resistance to adverse environmental factors and, accordingly, obtaining a consistently high yield. Carbon nanocompounds are perspective compounds for increasing plant stress resistance. They have high biocompatibility, which opens up wide prospects for their use, in particular in crop production. Considering the above, we conducted an analysis of modern scientific research on the use of carbon nanomaterials as stress resistance regulators in plants.

1. The mechanisms of penetration of carbon nanoparticles into plant cells and their influence on physiological and biochemical processes

Carbon nanoparticles (fullerenes, nanotubes, graphene) are widely studied as perspective compounds for using in the medical and pharmacological fields[9, 10, 11], which can carry out targeted delivery of drugs, including

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[5] Kolupaev Yu. E., Karpets Yu. V. Role of signal mediators and stress hormones in regulation of plants antioxidative system. *Fiziol. rast. genet.* 2017. Vol. 49, № 6. P. 463–481. DOI: 10.15407/frg2017.06.463

[6] Iqbal M. S., Singh A. K., Ansari M. I. Effect of Drought Stress on Crop Production. Springer. 2020. Singapore: Vol. 35. DOI: 10.1007/978-981-15-1322-0_3

[7] Kumari V. V., Banerjee P., Verma V. C., Sukumaran S., Chandran M. A. S., Gopinath K. A., Venkatesh G., Yadav S. K., Singh V. K., Awasthi N. K. Plant Nutrition: An Effective Way to Alleviate Abiotic Stress in Agricultural Crops. *Int J Mol Sci.* 2022. Vol. 23, № 15. 8519. DOI: 10.3390/ijms23158519.

[8] Esmaeili N., Shen G., Zhang H. Genetic manipulation for abiotic stress resistance traits in crops. *Front. Plant Sci*. 2022. Vol. 13. DOI: 10.3389/fpls.2022.1011985

[9] Prylutska S. V., Burlaka A. P., Klymenko P. P., Grynyuk, I. I. Prylutskyy Y. I.,. Schütze C., Ritter U. Using water-soluble C60 fullerenes in anticancer therapy. *Cancer Nano*. 2011. Vol. 2. 105–110. DOI: 10.1007/s12645-011-0020-x

[10] Rodríguez-Lozano F. J., García-Bernal D., Aznar-Cervantes S., Oñate-Sánchez R. E., Moraleda J. M. Potential of graphene for tissue engineering applications. *Transl Res*. 2015. Vol. 166, № 4. P. 399–400. DOI: 10.1016/j.trsl.2015.04.003

[11] Debnath S. K., Srivastava R. Drug Delivery With Carbon-Based Nanomaterials as Versatile Nanocarriers: Progress and Prospects. Front. *Nanotechnol*. 2021. Vol. 3. DOI: 10.3389/fnano.2021.644564

anticancer drugs, restore damaged cells and structures, in particular synapses, neurons, collagen fibers[12, 13, 14].

The effect of carbon nanoforms on plants is less studied, although, as evidenced by the data of a few studies, the physical characteristics of nanomaterials, such as size, shape, solubility, surface features, dose, as well as the species, age, genotype of the plant, play a significant role in this process. method of applying nanocarbon, properties of the soil or nutrient medium[15, 16, 17, 18, 19, 20].

In recent years the research of interactions of the different types and structures of nanoparticles with plant and their use in agriculture has attracted a lot of interest[21, 22]. Due to the unique properties, nanomaterials can be used

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[12] Hu H., Ni Y. C., Mandal S. K., Montana V., Zhao N., Haddon R. C., V. Parpura. Polyethyleneimine functionalized single-walled carbon nanotubes as a substrate for neuronal growth. *J Phys Chem B*. 2005. Vol. 109. P. 4285–4289. doi: 10.1021/jp0441137

[13] Qian L., Chengfei Y., Tao Ch., Changkun D., Z. Hongtian. Construction and characterization of conductive collagen/multiwalled carbon nanotube composite films for nerve tissue engineering. *AIP Advances*. 2022. Vol. 12, № 5. DOI: 10.1063/5.0090006

[14] MacDonald R. A., Laurenzi B. F., Viswanathan G., Ajayan P. M., Stegemann J. P. Collagen-carbon nanotube composite materials as scaffolds in tissue engineering. *Journal of Biomedical Materials Research.* 2005. Vol. 74 A, № 3. P. 489–496. DOI: 10.1002/jbm.a.30386

[15] Tripathi D. K., Gaur S., Singh S., Singh S., Pandey R., Singh V. P., Sharma N. C., Prasad S. M., Dubey N. K., Chauhan D. K. *Plant Physiology et Biochemistry*. 2016. Vol. 110, № 2. DOI: 10.1016/j.plaphy.2016.07.030.

[16] Serag M. F., Kaji N., Habuchi S., Bianco A., Baba Y. Nanobiotechnology meets plant cell biology: carbon nanotubes as organelle targeting nanocarriers. *RSC Adv*. 2013. Vol. 3. P. 4856–4862. DOI: 10.1039/c2ra22766e.

[17] Begum P, Ikhtiari R., Fugetsu B., Matsuoka M., Akasaka T., Watari F. Phytotoxicity of multi-walled carbon nanotubes assessed by selected plant species in the seedling stage. *Applied Surface Science*. 2012. Vol. 262. P. 120–124. DOI: 10.1016/j.apsusc.2012.03.028

[18] Prylutska S. V., Franskevych D. V., Yemets A. I. Cellular biological and molecular genetic effects of carbon nanomaterials in plant. *Cytol Genet*. 2022. Vol. 56, № 4. P. 351–360. DOI: 10.3103/S0095452722040077

[19] Wang Y., Shu Z., Wang W., Jiang X., Li D., Pan J., Li X. CsWRKY2, a novel WRKY gene from Camellia sinensis, is involved in cold and drought stress responses. *Biol. Plant*. 2016. Vol. 60. P. 443–451. DOI: 10.1007/s10535-016-0618-2

[20] Galbraith D. W. Nanobiotechnology: silica breaks through in plants. *Nat Nanotechnol.* 2007. Vol. 2 (5). P. 272–273. DOI: 10.1038/nnano.2007.118.

[21] Torney, F., Trewyn, B., Lin, VY. Wang K. Mesoporous silica nanoparticles deliver DNA and chemicals into plants. *Nature Nanotech.* 2007. Vol. 2. P. 295–300. DOI: 10.1038/nnano.2007.108

[22] Lahiani M. H., Dervishi E., Chen J., Nima Z., Gaume A., Biris A. S., Khodakovskaya M. V. Impact of carbon nanotube exposure to seeds of valuable crops. *ACS Appl Mater Interfaces*. 2013 Vol. 5 (16). P. 7965–7973. DOI: 10.1021/am402052x.

as pesticides, seed/plant growth enhancers, and carriers of herbicides, fertilizers, DNA, and phytohormones into plant cells[23, 24].

Carbon nanotubes. The length and diameter of single-walled carbon nanotubes are the main parameters that determines the penetration of carbon nanoparticle into a plant cell. Nanosized of carbon nanoparticle is lead to their rapid removal from the cell, and macrosized of its is lead to immobilized fixation in the cytoplasm or intercellular space[25].

Multi-walled carbon nanotubes (5 mg/ml) at exogenously treatment are absorbed by tomato seedlings and are distributed in the cells of their roots. According to other data, at the presence of multi-walled carbon nanotubes in the soil leads to their distribution not only in the roots, but also in other organs, including fruits and leaves[26, 27].

Authors (Lahiani et al, 2016) showed that multi-walled carbon nanotubes (MWCNTs) and graphene at a concentration of 50 μg/mL in the *in vitro* and *in vivo* experiments activated cell growth, germination, and growth of tobacco callus culture[28].

Carbon nanotubes have prospects for using in genetic engineering of plants. A complex of single-walled carbon nanotubes with chitosan was synthesized. This complex deliverd plasmid DNA to the chloroplasts of various species of mature plants (Nasturtium officinale, Nicotiana tabacum, Eruca sativa, Spinacia oleracea) without using traditional biolytic or chemical methods[26].

The distribution of single-walled carbon nanotubes in protoplasts depends on their size, but not zeta potential indexes. At the same time, nanotubes containing DNA have a better interaction with glycerolipids of chloroplast membranes compared to phospholipids. Cells whose protoplasts contain more

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[23] Bianco A., Kostarelos K., Partidos Ch. D., Prato M. Biomedical applications of functionalised carbon nanotubes. *Chemical Communications*. 2005. № 5. P. 571–577. DOI: 10.1039/B410943K

[24] Cao Z., Zhou H., Kong L., Li L., Wang R., Shen W. A. Novel Mechanism Underlying Multi-walled Carbon Nanotube-Triggered Tomato Lateral Root Formation: the Involvement of Nitric Oxide. *Nanoscale Res Lett*. 2020. Vol. 15 (1). DOI: 10.1186/s11671-020-3276-4

[25] Serag M. F., Kaji N., Habuchi S., Bianco A., Baba Y. Nanobiotechnology meets plant cell biology: carbon nanotubes as organelle targeting nanocarriers. *RSC Adv*. 2013. Vol. 3. P. 4856–4862. DOI: 10.1039/c2ra22766e.

[26] Khodakovskaya M. V., De Silva K., Biris A. S., Dervishi E., Villagarcia H. Carbon nanotubes induce growth enhancement of tobacco cells. *ACS nano*. 2012. Vol. 6, № 3. P. 2128–2135. DOI: 10.1021/nn204643g

[27] Kwak S.-Y., T. T. S. Lew, C. J. Sweeney, V. B. Koman, M. H. Wong, K. Bohmert-Tatarev, K. D. Snell, J. S. Seo, N. H. Chua, and M. S. Strano, Nat. *Nanotechnol*. 2019. № 14 (5). P. 447. DOI: 10.1038/s41565-019-0375-4

[28] Lahiani M. H., Dervishi E., Chen J., Nima Z., Gaume A., Biris A. S., Khodakovskaya M. V. Impact of carbon nanotube exposure to seeds of valuable crops. *ACS Appl Mater Interfaces.* 2013 Vol. 5 (16). P. 7965–7973. DOI: 10.1021/am402052x.

chloroplasts (mesophyll, closing cells) are more favorable for the internalization of single-walled carbon nanotubes compared to epidermal cells, which have fewer chloroplasts[29].

According to Giraldo et al.[30], the penetration of single-walled carbon nanotubes through the chloroplast membrane is due to their interaction with glycerolipids, which envelop the nanoparticles. Due to the destruction of the chloroplast membrane, lipids are adsorbed on the hydrophobic surface of carbon nanotubes and thus bind to the inner part of chloroplasts. Carbon nanotubes undergo kinetic absorption by lipids, and the chloroplast membrane is subsequently restored again.

Spray treatment of plants by a solution of single-walled carbon nanotubes caused the micromorphology changes of leaves and also changes of the structural and functional properties of chloroplasts. Single-walled carbon nanotubes at a concentration of 300 mg/L caused increasing the layer of epicuticular wax on the outer/inner surface of the leaves. The authors suggest that such changes in leaves are caused by mechanical stress similar to that caused by insects. At the same time, nanotubes in chloroplasts cause the swelling of lamellae and thylakoids, which ultimately leads to a decrease in the number of photochemically active centers of PSII and inhibition of the photosynthesis process[31].

Single-walled carbon nanotubes at a concentration of 25 μg/ml showed toxic effects on the protoplasts of japanese rice (*Oryza sativa subsp. japonica*) and arabidopsis thaliana (*Arabidopsis thaliana*). Critical parameters of toxicity of carbon nanoparticles are their nanosize, concentration and number of clusters formed. The death of protoplasts (approximately 25 %) is observed at 6 hours after treatment and occured through apoptos depended ways. Cells that remain at a distance from nanoparticles retain their viability[32].

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[29] Lew T. T. S., Wong M. H., Kwak S.-Y., Sinclair R., Koman V. B., Strano M. S. Rational Design Principles for the Transport and Subcellular Distribution of Nanomaterials into Plant Protoplasts. *Small*. 2018. Vol. 14 (44). DOI:10.1002/smll.201802086

[30] Giraldo J. P., Landry M. P., Faltermeier S. M., Mc Nicholas T. P., Iverson N. M., Boghossian A. A., Reuel N. F., Hilmer A. J., Sen F., Brew J. A., Strano M. S. Plant nanobionics approach to augment photosynthesis and biochemical sensing. *Nat Mater*. 2014. Vol. 13 (4). P. 400–408. DOI: 10.1038/nmat3890

[31] Velikova V., Petrova N., Kovács L., Petrova A., Koleva D., Tsonev T., Taneva S., Petrov P., Krumova S. Single-Walled Carbon Nanotubes Modify Leaf Micromorphology, Chloroplast Ultrastructure and Photosynthetic Activity of Pea Plants. *Int J Mol Sci.* 2021. Vol. 22 (9). DOI:10.3390/ijms22094878

[32] Shen C. X., Zhang Q. F., Li J., Bi F. C., Yao N. Induction of programmed cell death in Arabidopsis and rice by single-wall carbon nanotubes. *Am J Bot.* 2010. Vol. 97 (10). P. 1602–1609. DOI: 10.3732/ajb.1000073

Regarding the toxicity of multi-walled carbon nanotubes for plants, research data is ambiguous. Some authors[33] noted the toxicity of multi-walled carbon nanotubes at concentrations 1000 and 2000 mg/L for the hydroponic culture of red spinach, lettuce, rice and cucumbers, which is manifested by a decrease in biomass, morphometric indicators in comparison with untreated plants.

According to other data[34], the growing catharanthus roseus (*Catharanthus roseus*) from seeds at the addition in the medium of multi-walled carbon nanotubes in concentration 50, 100 and 150 mg/L, on the contrary, caused the increasing the width and area of leaves, total biomass, root length, content in seedlings of carotenoids, chlorophyl *a* and *b*, protein, activity of catalase and peroxidase and soluble phenols and alkaloids. The content of multi-walled carbon nanotubes 100–150 mg/L in the cultivation medium stimulated the callusogenesis process. Other authors also note that multi-walled carbon nanotubes stimulated the growth and development of broccoli and corn plants[35, 36, 37, 38].

The effect of carbon nanoparticles also depends on their concentration. For example, beans grown in hydroponics were resistant to the action of multi-walled carbon nanotubes at a concentration of 50 μg/ml, at the same time, at higher doses (250, 500 μg/ml) caused a slowdown in the growth and development of plants and even their death[39].

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[33] Begum P, Ikhtiari R., Fugetsu B., Matsuoka M., Akasaka T., Watari F. Phytotoxicity of multi-walled carbon nanotubes assessed by selected plant species in the seedling stage. *Applied Surface Science.* 2012. Vol. 262. P. 120–124. DOI: 10.1016/j.apsusc.2012.03.028

[34] Ghasempour M., Iranbakhsh A., Ebadi M., Oraghi Ardebili Z. Multi-walled carbon nanotubes improved growth, anatomy, physiology, secondary metabolism, and callus performance in Catharanthus roseus: an in vitro study. *3 Biotech*. 2019. Vol. 9 (11). DOI: 10.1007/s13205-019-1934-y

[35] Martínez-Ballesta M. C., Zapata L., Chalbi N., Carvajal M. Plant nanobionics approach to augment photosynthesis and biochemical sensing. *J Nanobiotechnol.* 2016. Vol. 14. DOI: 10.1186/s12951-016-0199-4

[36] Tiwari D. K., Dasgupta-Schubert N., Villaseñor Cendejas L. M., Villegas J., Carreto Montoya L., Borjas García S. E. Interfacing carbon nanotubes (CNT) with plants: enhancement of growth, water and ionic nutrient uptake in maize (Zea mays) and implications for nanoagriculture. *Appl Nanosci*. 2014. Vol. 4. 577–591. DOI: 10.1007/s13204-013-0236-7

[37] Hao Y., Yu Y., Sun G., Gong X., Jiang Y., Lv G., Zhang Y., Li L., Zhao Y., Sun D.,

Gu W., Qian C. Single-Walled Carbon Nanotubes Modify Leaf Micromorphology, Chloroplast Ultrastructure and Photosynthetic Activity of Pea Plants. *Plants.* 2023. Vol. 12, № 8. DOI: 10.3390/plants12081604

[38] Oliveira H. C., Seabra A. B., Kondak S., Adedokun O. P., Kolbert Z. Multilevel approach to plant-nanomaterial relationships: from cells to living ecosystems. *Journal of Experimental Botany*. 2023. Vol. 74, № 12. P. 3406–3424. DOI:10.1093/jxb/erad107

[39] Keita K., Okafor F. C., Nyochembeng L. M., Overton A., Sripathi V. R., Odutola J. A. Plant and Microbial Growth Responses to Multi-Walled Carbon Nanotubes. *J Nanosci Curr Res.* 2018. Vol. 3. DOI: 10.4172/2572-0813.1000123

Nanomaterials of industrial origin in the environment are combined with a number of impurities that correct the manifestations of their biological effects. Multi-walled carbon nanotubes of industrial grade with catalyst impurities are adsorbed on the surface of alfalfa and wheat roots without absorption or translocation and contribute to the elongation of the latter, at the same time, they do not affect seed germination even at high doses (up to 2560 mg/L)[40].

C_{60} fullerenes and their derivatives. It is noted that fullerene C_{60} has low bioavailability in plants (~7 % $^{14}C_{60}$), the vast majority of nanoparticles of which accumulate in roots (40–47 %), tubers (22–23 %), less in stems (12–16 %) and leaves (18–22 %)[41].

These results are confirmed by other researchers[42]. They note the maximum dose- and time-dependent accumulation of labeled fullerenol in wheat roots. At the same time, it is noted that carbon nanoparticles at low concentrations of 2.5 µg/ml are accumulated but at high concentrations of its, on the contrary, suppress this process. Small amounts of fullerenol nanoparticles are transported to stems and leaves.

Using infrared spectroscopy by Fourier transform accumulation of fullerol in bitter melon (*Momordica charantia*) organs, including petioles, leaves, flowers, and fruits was observed. According to the authors, the absorption of fullerol in plants occurs due to transpiration, the emergence of a concentration gradient in the plant continuum, as well as the hydrophobic interaction between fullerol and the wax layer on the surface of plant cells[43].

After treatment of wheat seedlings by fullerene C_{60} solution was not showed acute phytotoxicity, but seriously blocked the pore structure of wheat roots even at short-term action. Using transmission electron microscopy and high-power optical microscopy compression the root endothelial cells with

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[40] Miralles P., Johnson E., Church T. L., Harris A. T. Multiwalled carbon nanotubes in alfalfa and wheat: toxicology and uptake. *J. R. Soc. Interface*. 2012. Vol. 9, № 77. P. 93514–93527. DOI: 10.1098/rsif.2012.0535

[41] Avanasi R., Jackson W. A., Sherwin B., Mudge J. F., Anderson T. A. C60 fullerene soil sorption, biodegradation, and plant uptake. *Environ. Sci. Technol.* 2014. Vol. 48 (5). P. 2792–2797. DOI: 10.1021/es405306w

[42] Wang Ch., Zhang H., Ruan L., Chen L., Li H., Chang X.-L., Zhang X., Yang S.-T. Bioaccumulation of 13C-fullerenol nanomaterials in wheat. *Environ. Sci.: Nano*. 2016. Vol. 4 (3). 799–805. DOI: 10.1039/C5EN00276A

[43] Kole C., Kole P., Randunu K. M., Choudhary P., Podila R., Ke P. C., Rao A. M., Marcus R. K. Nanobiotechnology can boost crop production and quality: first evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (Momordica charantia). *BMC Biotechnol*. 2013. Vol. 13. DOI: 10.1186/1472-6750-13-37

damage to the structure of their inner wall due to nanoparticle extrusion was detected[44].

After treatment of rice plants with fullerene C_{60} at a concentration of 600 mg/kg during 130 days was detected that nanoparticles were absorbed by rice roots and entered into the stems and panicles, while forming aggregates in the tissues[45].

Some authors noted the toxic effect of fullerenol on rice plants. The treatment of rice with C_{60} nanoparticles at a concentration of 20 mg/L and 100 mg/L reduced the concentration of phytohormones: dihydrozeatin riboside by 23 and 18 %, zeatin riboside by 23 % and 18 %, abscisic acid by 11.1 % and 12.7 %, brassinolide by 12.9 % and 13.1 %, gibberellic acid 4 by 12.9 % and 13.1 %, respectively, in comparison with the control[46].

However, an increase in the following phytohormones such as gibberellic acid 3 (7 %) and methyljasmonic acid (19.4 %) in rice plants after treatment with fullerene C_{60} at a dose of 100 mg/L was noted[47]. Other researchers have shown that fullerene derivatives, polyhydroxyfullerenes (fullerol, fullerenol) not only do not cause a toxic effect on plants, but also have a positive effect, in particular, increasing the density of algae culture[48].

Graphene, graphene oxide. Among carbon nanomaterials, it is graphene and graphene oxide that have the widest industrial application[49]. Their influence on the organism of plants of various species is studied almost the most actively. There are data on the effect of graphene and its derivatives on

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[44] He A., Jiang J., Ding J., Sheng G. D. Blocking effect of fullerene nanoparticles (nC60) on the plant cell structure and its phytotoxicity. *Chemosphere*. 2021. Vol. 278. DOI: 10.1016/j.chemosphere.2021.130474

[45] Liang C., Xiao H., Hu Z., Zhang X., Hu J. Uptake, transportation, and accumulation of C60 fullerene and heavy metal ions (Cd, Cu, and Pb) in rice plants grown in an agricultural soil. *Environ Pollut*. 2018. Vol. 235. P. 330–338. DOI: 10.1016/j.envpol.2017.12.062

[46] Guo K. R., Adeel M., Hu F., Xiao Z. Z., Wang K. X., Hao Y., Rui Y. K., Chang X. L. Absorption of Carbon-13 Labelled Fullerene (C60) on Rice Seedlings and Effect of Phytohormones on Growth. *J Nanosci Nanotechnol*. 2021. Vol. 21 (6). P. 3197–3202. DOI: 10.1166/jnn.2021.19307

[47] Guo K. R., Adeel M., Hu F., Xiao Z. Z., Wang K. X., Hao Y., Rui Y. K., Chang X. L. Absorption of Carbon-13 Labelled Fullerene (C60) on Rice Seedlings and Effect of Phytohormones on Growth. *J Nanosci Nanotechnol*. 2021. Vol. 21 (6). P. 3197–3202. DOI: 10.1166/jnn.2021.19307

[48] Gao J., Wang Y., Folta K. M., Krishna V., Bai W., Indeglia P., Georgieva A., Nakamura H., Koopman B., Moudgil B. Polyhydroxy fullerenes (fullerols or fullerenols): beneficial effects on growth and lifespan in diverse biological models. *PLoS One*. 2011. Vol. 6 (5). DOI: 10.1371/journal.pone.0019976.

[49] Chen L., Wang C., Li H., Qu X., Yang S., Chang X. Bioaccumulation and Toxicity of 13C-Skeleton Labeled Graphene Oxide in Wheat. *Environmental science & technology*. 2017. Vol. 51, № 17. P. 10146–10153. DOI: 10.1021/acs.est.7b00822

rice[50], common oats[51], white clover[52], marsh cocks[53], wheat[54], rapeseed[55], cabbage, red spinach, lettuce[56], tomatoes[57], corn[58, 59], strawberries[60], aloe vera[61].

After action of graphene oxide at low concentrations on Arabidopsis thaliana (*Arabidopsis thaliana*) was not showed significant accumulation of nanoparticles in the cells of the mesophyll, parenchyma, sieve-like elements of leaves and stems, however, the accumulation was significant in root hairs and cells of the root parenchyma[62].

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[50] Huang C., Xia T., Niu J., Yang Y., Lin S., Wang X., Yang G., Mao L., Xing B. Transformation of 14 C-Labeled Graphene to 14 CO2 in the Shoots of a Rice Plant. *Angewandte Chemie*. 2018. Vol. 57, № 31. P. 9759–9763. DOI: 10.1002/anie.201805099

[51] Chen L., Yang S., Liu Y., Mo M., Guan X., Huang L., Sun C., Yang S., Chang X. Toxicity of graphene oxide to naked oats (Avena sativa L.) in hydroponic and soil cultures. *RSC Advances*. 2018. Vol. 8 (28). P. 15336–15343. DOI: 10.1039/c8ra01753k.

[52] Zhao S., Zhu X., Mou M., Wang Z., Duo L. Assessment of graphene oxide toxicity on the growth and nutrient levels of white clover (Trifolium repens L.). *Ecotoxicology and environmental safety*. 2022. Vol. 234. DOI: 10.1016/j.ecoenv.2022.113399

[53] Zhou Z., Li J., Li C., Guo Q., Hou X., Zhao C., Wang Y., Chen C., Wang Q. ffects of Graphene Oxide on the Growth and Photosynthesis of the Emergent Plant Iris pseudacorus. *Plants*. 2023. Vol. 12 (9). DOI: 10.3390/plants12091738.

[54] Chen L., Wang C., Li H., Qu X., Yang S., Chang X. Bioaccumulation and Toxicity of 13C-Skeleton Labeled Graphene Oxide in Wheat. *Environmental science & technology*. 2017. Vol. 51. № 17. P. 10146–10153. DOI: 10.1021/acs.est.7b00822

[55] Xiao X., Wang X., Liu L., Chen C., Sha A., Li J. Effects of three graphene-based materials on the growth and photosynthesis of Brassica napus L. *Ecotoxicology and environmental safety*. 2022. Vol. 234. DOI: 10.1016/j.ecoenv.2022.113383

[56] Begum P., Ikhtiari R., Fugetsu B. Graphene phytotoxicity in the seedling stage of cabbage, tomato, red spinach, and lettuce. *Carbon*. 2011. Vol. 49. P. 3907–3919. DOI: 10.1016/j.carbon.2011.05.029

[57] Guo X., Zhao J., Wang R., Zhang H., Xing B., Naeem M., Yao T., Li R., Xu R. F., Zhang Z., Wu J. Effects of graphene oxide on tomato growth in different stages. *PPB*. 2021. Vol. 162. P. 447–455. DOI: 10.1016/j.plaphy.2021.03.013

[58] Ren W., Chang H., Teng Y. Sulfonated graphene-induced hormesis is mediated through oxidative stress in the roots of maize seedlings. *Sci Total Environ*. 2016. Vol. 572. P. 926–934. DOI: 10.1016/j.scitotenv.2016.07.214

[59] Chen Z., Zhao J., Song J., Han S., Du Y., Qiao Y., Liu Z., Qiao J., .Li W., Li J., Wang H., Xing B., Pan Q. Influence of graphene on the multiple metabolic pathways of Zea mays roots based on transcriptome analysis. *PloS one*. 2021. Vol. 16, № 1. DOI: 10.1371/journal.pone.0244856

[60] Malekzadeh M. R., Roosta H. R., Kalaji H. M. GO nanoparticles mitigate the negative effects of salt and alkalinity stress by enhancing gas exchange and photosynthetic efficiency of strawberry plants. *Sci Rep*. 2023. Vol. 13. DOI: 10.1038/s41598-023-35725-0

[61] Zhang X., Cao H., Zhao J., Wang H., Xing B., Chen Z., Li X., Zhang J. Graphene oxide exhibited positive effects on the growth of Aloe vera L. *Physiology and Molecular Biology of Plants*. 2021. Vol. 27. P. 815–824. DOI: 10.1007/s12298-021-00979-3

[62] Zhao S., Wang Q., Zhao Y., Rui Q., Wang D. Toxicity and translocation of graphene oxide in Arabidopsis thaliana. *Environ Toxicol Pharmacol*. 2015. Vol. 39 (1). 145–156. DOI: 10.1016/j.etap.2014.11.014

Cultivation of wheat (*Triticum aestivum L.*) on a hydroponic medium with ^{14}C-labeled graphene led to its penetration into the roots and stems, where it moves between neighboring cells along the symplast. The penetration of graphene into root cells occurs through the tips of root hairs, which have thinner primary cell walls[63].

The addition of ^{13}C-labeled graphene oxide at a dose of 1.0 mg/ml to the nutrient medium where wheat was grown after 15 days caused to the accumulation of the nanostructure mainly in the roots, but with limited translocation to the stem and leaves[64].

Xiao et al.[65] established that graphene oxide causes ruptures and blurring of the cell walls of rapeseed roots with signs of plasmolysis and the absence of changes in the structure of organoids, as well as the accumulation of nanoparticles in the intercellular space.

Regarding the toxicity of graphene and its derivatives, the existing research data of various authors is ambiguous. Some authors[66] noted that the content of graphene in the soil at concentration 50 g/kg stimulated plant growth and improved the assimilation of nutrients by corn plants, which is confirmed by an increase in the content of potassium, phosphorus and total nitrogen in the stem and leaves.

Mirza *et al.*[67] also observed a positive effect of graphene oxide on the growth processes of *Vigna radiata L.*, manifested by an increase in the length of roots and shoots, the number of root nodules, leaves, pods and seeds in a pod. In strawberry plants, graphene oxide contributed to an increase in the content of photosynthetic pigments, an increase in yield and an increase in dry biomass.

However, other studies indicate about negative effects of graphene on plant growth and development. Graphene at a dose of 50, 100, 200 mg/L impaired the germination of rice seeds and reduced the length/weight of the

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[63] Dong S., Jing X., Lin S., Lu K., Li W., Lu J., Li M., Gao S., Lu S., Zhou D., Chen C., Xing B., Mao L. Root Hair Apex is the Key Site for Symplastic Delivery of Graphene into Plants. *Environ Sci Technol*. 2022. Vol. 56, № 17. P. 12179–12189. DOI: 10.1021/acs.est.2c01926.

[64] Chen L., Wang C., Li H., Qu X., Yang S., Chang X. Bioaccumulation and Toxicity of 13C-Skeleton Labeled Graphene Oxide in Wheat. *Environmental science & technology*. 2017. Vol. 51, № 17. P. 10146–10153. DOI: 10.1021/acs.est.7b00822

[65] Xiao X., Wang X., Liu L., Chen C., Sha A., Li J. Effects of three graphene-based materials on the growth and photosynthesis of Brassica napus L. *Ecotoxicology and environmental safety.* 2022. Vol. 234. DOI: 10.1016/j.ecoenv.2022.113383

[66] Wang S., Liu Y., Wang X., Xiang H., Kong D., Wei N., Guo W., Sun H. Effects of concentration-dependent graphene on maize seedling development and soil nutrients. *Sci Rep.* 2023. Vol. 13 (1). DOI: 10.1038/s41598-023-29725-3A.

[67] Mirza F. S., Aftab Z. E., Ali M. D., Aftab A., Anjum T., Rafiq H., Li G. Green synthesis and application of GO nanoparticles to augment growth parameters and yield in mungbean (Vigna radiata L.). *Front Plant Sci*. 2022. Vol. 13. DOI: 10.3389/fpls.2022.1040037

root and stem[68]. A concentration of graphene oxide of 1.0 mg/ml slows down the development and growth of wheat, contributes to the development of oxidative stress, damage to the cellular structure and ultrastructure is noted in plant roots[69, 70]. Graphene oxide at a dose of 0.01–1.0 mg/L in hydroponic rice culture induced a decrease in hydraulic conductivity and aquaporin gene expression, as well as oxidative stress[71]. Graphene oxide suppresses the diversity and number of endophytic bacterial populations in rice roots[72].

Thus, summarizing the results of research by various authors, it can be concluded that the effect of carbon nanoparticles on the plant organism is determined by the shape, surface characteristics, size, solubility, dose/concentration of nanomaterials, as well as the conditions and terms of processing, features of the nutrient medium or soil, genotype and age of the plant. Predominantly low concentrations of nanoparticles stimulate seed germination, growth and development of vegetative parts of the plant and roots, improve the efficiency of photosynthesis, protect plants from the effects of environmental stress factors. In contrast, nanoparticles at high concentrations caused a toxic effect on plant cells, which is accompanied by a slowdown in growth, plant development and synthesis processes.

2. Stress resistance of various types of plants after the action of carbon nanoparticles

Unfavorable factors of the environment cause the development of stress in plants. In view of global climate changes, crop production suffers more and more as a result of the complex of abiotic and biotic stresses, which significantly affects the yield of the main agricultural crops and its quality. It is nanotechnologies that are promising and ecological means of activating

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[68] Liu S., Wei H., Li Z., Li S., Yan H., He Y., Tian Z. Effects of Graphene on Germination and Seedling Morphology in Rice. *J Nanosci Nanotechnol*. 2015. Vol. 15 (4). DOI: 10.1166/jnn.2015.9254

[69] Chen L., Wang C., Li H., Qu X., Yang S., Chang X. Bioaccumulation and Toxicity of 13C-Skeleton Labeled Graphene Oxide in Wheat. *Environmental science & technology*. 2017. Vol. 51, № 17. P. 10146–10153. DOI: 10.1021/acs.est.7b00822

[70] Du J., Wang T., Zhou Q., Hu X., Wu J., Li G., Li G., Hou F., Wu Y. Graphene oxide enters the rice roots and disturbs the endophytic bacterial communities. *Ecotoxicol Environ Saf*. 2020. Vol.192. DOI: 10.1016/j.ecoenv.2020.110304

[71] Zhou Q., Hu X. Systemic Stress and Recovery Patterns of Rice Roots in Response to Graphene Oxide Nanosheets. *Environ Sci Technol*. 2017. Vol. 51 (4). DOI: 10.1021/acs.est.6b05591

[72] Du J., Wang T., Zhou Q., Hu X., Wu J., Li G., Li G., Hou F., Wu Y. Graphene oxide enters the rice roots and disturbs the endophytic bacterial communities. *Ecotoxicol Environ Saf*. 2020. Vol.192. DOI: 10.1016/j.ecoenv.2020.110304

secondary plant metabolism, mechanisms of adaptation and evolution as protection against changed environmental conditions[73, 74, 75, 76].

Carbon nanotubes. Broccoli seedlings grown on an synthetic medium with simulated salinity by NaCl (100 mM) and the simultaneous addition of multi-walled carbon nanotubes at a dose of 10 mg/L tolerate salt stress better in comparison with control group. It should be noted that the presence of carbon nanoparticles increases the number of aquaporin proteins that form specific pores for water transport. Thus, the roots have a higher hydraulic conductivity[77].

According to the research[78], cell growth and genes activity of tobacco cell culture that control cell division/cell wall formation and water transport directly depend on the addition of multi-walled carbon nanotubes to the culture medium. The authors noted increased expression of the tobacco aquaporin gene (*NtPIP1*), the cell division marker gene *CycB*, and the cell elongation and cell wall formation gene *NtLRX1*.

The germination of corn seeds on a gel medium with the addition of multi-walled carbon nanotubes increases the porosity of the pericarp and seed coat, including due to the delamination of their structure, which is detected by scanning electron microscopy of the surface. It is assumed that the formation of pores is the factor that contributes to the influx of water, nutrients, oxygen, as well as the dispersion of the aqueous phase of multilayer carbon nanotubes into the germinating seed. At the same time, the most effective concentration of carbon nanotubes is 20 mg/L[79].

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[73] Bradshaw D., Hardwick K. Evolution and stress – genotypic and phenotypic components. *Biological Journal of the Linnean Society*. 1989. Vol. 37, № 1–2. P. 137–155. DOI:10.1111/j.1095-8312.1989.tb02099.x

[74] Chen Z., Soltis D. E. Evolution of environmental stress responses in plants. *Plant, Cell and Environment.* 2020. Vol. 43. P. 2827–2831. DOI: 10.1111/pce.13922

[75] Cramer G. R., Urano K., Delrot S., Pezzotti M., Shinozaki K. Effects of abiotic stress on plants: a systems biology perspective. *BMC Plant Biol.* 2011. Vol. 11. DOI: 10.1186/1471-2229-11-163

[76] Fahad S., Bajwa A. A., Nazir U., Anjum S. A., Farooq A., Zohaib A., Sadia S., Nasim W., Adkins S., Saud S., Ihsan M. Z., Alharby H., Wu C., Wang D., Huang J. Crop Production under Drought and Heat Stress: Plant Responses and Management Options. *Front. Plant Sci.* 2017. Vol. 8. DOI: 10.3389/fpls.2017.01147

[77] Martínez-Ballesta M. C., Zapata L., Chalbi N., Carvajal M. Plant nanobionics approach to augment photosynthesis and biochemical sensing. *J Nanobiotechnol.* 2016. Vol. 14. DOI: 10.1186/s12951-016-0199-4

[78] Khodakovskaya M. V., De Silva K., Biris A. S., Dervishi E., Villagarcia H. Carbon nanotubes induce growth enhancement of tobacco cells. *ACS nano*. 2012. Vol. 6, № 3. P. 2128–2135. DOI: 10.1021/nn204643g

[79] Tiwari D. K., Dasgupta-Schubert N., Villaseñor Cendejas L. M., Villegas J., Carreto Montoya L., Borjas García S. E. Interfacing carbon nanotubes (CNT) with plants: enhancement of growth, water and ionic nutrient uptake in maize (Zea mays) and implications for nanoagriculture. *Appl Nanosci*. 2014. Vol. 4. 577–591. DOI: 10.1007/s13204-013-0236-7

The treatment of corn with a nanosuspension of multi-walled carbon nanotubes of corn in the phase of three leaves caused a decrease reactive oxygen species, in particular, hydrogen peroxide and superoxide anion radical. The most effective concentration of nanoparticles is 800 mg/L. After treatment corn seedlings with multi-walled carbon nanotubes at concentration 800 mg/L was indicated increase of the activity of the main enzymes of photosynthesis and enzymes of nitrogen metabolism, stimulation of the opening of stomata, and improvement of the efficiency of CO_2 fixation related to nitrogen metabolism in plants. A high concentration of multi-walled nanotubes (1200 mg/L) caused clogging of the root pores of corn[80].

According to a study by Samadi *et al.*[81], single-walled carbon nanotubes at low concentrations (25, 50, 100 μg/ml) stimulated the synthesis of bioactive compounds of thyme (*Thymus daenensis*), the development of its callus, and antioxidant activity. These nanoparticles activated antioxidant enzymes, namely polyphenol oxidase, phenylalanine-ammonia-lyase, dehydrogenase and peroxidase. Considering that thyme is a medicinal herbs, an important effect for the using of carbon nanoparticles is an increase in the content of pharmacologically active compounds in plants – phenols, flavonoids, rosmarinic and trans-ferulic acids, catechin, hesperedin, vanillin, carvacrol.

Other authors who studied the effect of drought stress, simulated by polyethylene glycol, on the germination of the seeds of the black henbane (*Hyoscyamus niger*) and found a decrease in its manifestations to a moderate level under the influence of low concentrations (50, 100 μg/ml) of single-walled carbon nanotubes. In the authors' opinion, such a protective effect is associated with increased water absorption by the seeds of the black henbane, activation of α-amylase, reduction of indicators of oxidative stress, namely the concentration of hydrogen peroxide and malondialdehyde. Changes in the expression of antioxidant enzymes, such as ascorbate peroxidase, peroxidase, superoxide dismutase, catalase, and enzymes for the synthesis of proline, phenols, and proteins were also noted[82].

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[80] Hao Y., Yu Y., Sun G., Gong X., Jiang Y., Lv G., Zhang Y., Li L., Zhao Y., Sun D., Gu W., Qian C. Single-Walled Carbon Nanotubes Modify Leaf Micromorphology, Chloroplast Ultrastructure and Photosynthetic Activity of Pea Plants. *Plants*. 2023. Vol. 12, № 8. DOI: 10.3390/plants12081604

[81] Samadi S., Saharkhiz M. J., Azizi M., Samiei L., Karami A., Ghorbanpour M. Single-wall carbon nano tubes (SWCNTs) penetrate Thymus daenensis Celak. plant cells and increase secondary metabolite accumulation in vitro. *Industrial Crops and Products*. 2021. Vol. 165. DOI:10.1016/j.indcrop.2021.113424

[82] Hatami M., Hadian J., Ghorbanpour M. Mechanisms underlying toxicity and stimulatory role of single-walled carbon nanotubes in Hyoscyamus niger during drought stress simulated by polyethylene glycol. *J Hazard Mater*. 2017. Vol. 324 (Pt B). P. 306–320. DOI: 10.1016/j.jhazmat.2016.10.064

Interesting are the data about the use of carbon nanotubes under biotic stress, namely phytophthora of tomatoes. Treatment with this carbon nanoform led to a reduction in tomato morbidity and disease severity, as well as an increase in yield. Similarly to previous studies, an increase in the activity of the antioxidant system was detected, an increase the content of ascorbic acid, flavonoids and glutathione peroxidase enzyme activity in plants, as well as the efficiency of photosynthesis[83].

The use of multi-walled and single-walled carbon nanotubes, graphene, and activated carbon resulted in an increase the number and length of lateral roots, but this indicator is significantly higher in tomato plants incubated in the presence of multi-walled carbon nanotubes. However, these nanoparticles stimulated the formation of endogenous nitric oxide (NO), which is a downstream signaling molecule that controls the formation of lateral roots[84]. In addition, under the influence of multi-walled nanotubes in tomato leaves are expressed genes for response to stress, transport, cellular reactions, signal transmission, metabolic and biosynthetic processes. In tomato roots genes of cellular processes, stress reactions, transport, catabolic, metabolic and biosynthetic processes were activated. Among the stress genes are the heat shock protein gene, TDR3 protein, Dem2 protein, tomato aquaporin, and mitogen-activated protein kinase[85].

Fullerenes and their derivatives. Irrigation of cherry tomato seeds with a polyhydroxylated derivative of fullerene C_{60} – fullerol with a solution concentration of 200 mg/L led to an increase in the number of photosynthetic leaf pigments, plant growth rate, fruit size, and lycopene content. In addition, the expression of aquaporin genes in the plasma membrane increased, which improved the entry of water and dissolved substances into the plant. Also, fullerol improves the antioxidant properties of plants through increases the activity of catalase and peroxidase and decreases the activity of superoxide dismutase. According to the authors, the decrease in SOD activity is a consequence of the ability of hydroxyl-modified fullerol to scavenge superoxide radicals in tomato cells[86].

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[83] González-García Y., Cadenas-Pliego G., Alpuche-Solís Á. G., Cabrera R. I., Juárez-Maldonado A. Carbon Nanotubes Decrease the Negative Impact of Alternaria solani in Tomato Crop. *Nanomaterials* (Basel, Switzerland). 2021. Vol. 11 (5). DOI:10.3390/nano11051080

[84] Cao Z., Zhou H., Kong L., Li L., Wang R., Shen W. A. Novel Mechanism Underlying Multi-walled Carbon Nanotube-Triggered Tomato Lateral Root Formation: the Involvement of Nitric Oxide. *Nanoscale Res Lett.* 2020. Vol. 15 (1). DOI: 10.1186/s11671-020-3276-4

[85] Khodakovskaya M. V., De Silva K., Biris A. S., Dervishi E., Villagarcia H. Carbon nanotubes induce growth enhancement of tobacco cells. *ACS nano*. 2012. Vol. 6, № 3. P. 2128–2135. DOI: 10.1021/nn204643g

[86] Subotić A., Jevremović S., Milošević S., Trifunović-Momčilov M., Đurić M., Koruga Đ. Physiological Response, Oxidative Stress Assessment and Aquaporin Genes Expression of

Treatment of bitter melon seeds (*Momordica charantia*) with fullerol stimulates the increase of yield and biomass of plants, activates the synthesis of biologically active substances – cucurbitacin-B, lycopene, charantin, and insulin, which are in demand in pharmacy[87].

At cobalt stress, the modulatory effect of water-soluble fullerene derivatives on corn seedlings was realized through the removal of hydrogen peroxide from tissues by non-enzymatic/enzymatic systems associated with the ascorbate-glutathione cycle, by preserving the conversion of ascorbate, the ratio of glutathione/glutathione disulfide, as well as the redox state of glutathione. Fullerenes significantly reduced the inhibitory effect of cobalt on nitrogen assimilation, and also increased the activity of enzymes in corn chloroplasts, such as nitrate reductase, glutamate dehydrogenase, nitrite reductase, and glutamine synthetase[88].

According to research by Shafiq *et al*.[89] the use of fullerenol as a nanoprimer for wheat seeds grown under salt stress had positive results regarding allometric indicators. In primed wheat, yield increased, compared to the group grown under stress and not treated with fullerenol. Seeds obtained from nanoprimed wheat showed better germination, length and biomass of shoots and roots. In such plants, restoration of the net assimilation coefficient, reduction of oxidative stress indicators and optimization of the Na^+/K^+, Na^+/Ca^{2+} and Na^+/P ratios have been established.

According to other studies, fullerenol at foliarly treatment to sugar beet plants, changes its intracellular metabolism. Fullerenol nanoparticles are capable of attaching a large number of water molecules around the core, acting as a kind of osmolyte. It is assumed that the release of water occurs with a significant decrease in the osmotic potential of cells, when the force of diffusion exceeds the force of hydrogen bonds formed between fullerenol and water molecules. In addition, to the above-mentioned mechanism, in sugar beet leaves, drought stress causes an increase in such an osmolyte as proline,

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Cherry Tomato (Solanum lycopersicum L.) Exposed to Hyper-Harmonized Fullerene Water Complex. *Plants* (Basel). 2022. Vol. 11. № 21. DOI: 10.3390/plants11212810.

[87] Kole C., Kole P., Randunu K. M., Choudhary P., Podila R., Ke P. C., Rao A. M., Marcus R. K. Nanobiotechnology can boost crop production and quality: first evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (Momordica charantia). BMC Biotechnol. 2013. Vol. 13. DOI: 10.1186/1472-6750-13-37

[88] Ozfidan-Konakci C., Alp F. N., Arikan B., Balci M., Parmaksizoglu Z., Yildiztugay E., Cavusoglu H. The effects of fullerene on photosynthetic apparatus, chloroplast-encoded gene expression, and nitrogen assimilation in Zea mays under cobalt stress. *Physiol Plant.* 2022. Vol. 174, № 3. DOI: 10.1111/ppl.13720

[89] Shafiq F., Iqbal M., Ali M., Ashraf M. A. Fullerenol regulates oxidative stress and tissue ionic homeostasis in spring wheat to improve net-primary productivity under salt-stress. *Ecotoxicol Environ Saf.* 2021. Vol. 211. DOI: 10.1016/j.ecoenv.2021.111901

while in plants treated with fullerenol, the proline content did not change either in the leaves or in the roots[90].

After treatment of rapeseed with fullerol under conditions of drought stress, the content of abscisic acid in plants increased due to a decrease in the expression of its catabolic gene CYP707A3. Treatment of seeds with carbon nanoparticles of fullerol stimulated its germination, increased dry weight and the intensity of the process of photosynthesis in seedlings. Under conditions of water deficit, fullerol inhibited the accumulation of ROS in rapeseed leaves, increased the concentration of non-antioxidant substances and the activity of antioxidant enzymes[91]. Similar results were observed during the germination of fullerol-treated wheat seeds under drought conditions, in particular, the levels of ROS and MDA were significantly lower in comparison with control plants, and the activity of antioxidant enzymes, on the contrary, was higher[92].

Thus, leaves of young rapeseed plants under drought stress accumulate primary metabolites, such as monosaccharides, amino acids (proline, glutamine), which provide osmotic adaptation[93, 94]. At the same time, the content of carbohydrates in rapeseed plants treated with fullerol did not change, and amino acids even decreased, but the synthesis of phenols and flavonoids, such as luteolin and trans-3-coumaric acid increased[95].

Graphene oxide. The use of graphene oxide for the treatment of strawberry plants grown on a solid substrate in created stress conditions (salinity and alkalinity) had a positive effect on gas exchange indicators. In plants grown under salinity conditions, the use of nanoparticles at a dose of 5 mg/L increased the CO_2 assimilation rate, transpiration rate, stomatal conductance, and water use efficiency. For strawberry plants grown under increased

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[90] Farooq M., Wahid A., Kobayashi N., Fujita D., Basra S. M. A. Plant drought stress: effects, mechanisms and management. *Agronomy for Sustainable Development.* 2009. Vol. 29. P. 185–212. DOI:10.1051/agro:2008021

[91] Xiong J. L., Li J., Wang H. C., Zhang C. L., Naeem M. S. Fullerol improves seed germination, biomass accumulation, photosynthesis and antioxidant system in Brassica napus L. under water stress. *Plant Physiol Biochem.* 2018. Vol. 129. P. 130–140. DOI: 10.1016/j.plaphy.2018.05.026

[92] Kong H., Meng X., Akram N. A., Zhu F., Hu J., Zhang Z. Seed Priming with Fullerol Improves Seed Germination, Seedling Growth and Antioxidant Enzyme System of Two Winter Wheat Cultivars under Drought Stress. *Plants* (Basel). 2023. Vol. 12 (6). DOI: 10.3390/plants12061417

[93] Farooq M., Wahid A., Kobayashi N., Fujita D., Basra S. M. A. Plant drought stress: effects, mechanisms and management. *Agronomy for Sustainable Development*. 2009. Vol. 29. P. 185–212. DOI:10.1051/agro:2008021

[94] Xiong J. L., Ma N. Transcriptomic and Metabolomic Analyses Reveal That Fullerol Improves Drought Tolerance in Brassica napus L. *Int J Mol Sci*. 2022. Vol. 23. DOI: 10.3390/ijms232315304

[95] Ibid.

alkalinity, the effects of applying graphene oxide were identical, and the optimal dose was 5 and 10 mg/L[96].

In *Iris pseudacorus* plants treated with graphene oxide, the dry weight increased up to 84 %, the content of carotenoids and chlorophyll *a*/*b* increased up to 178 %, but the optimal concentration of nanoparticles was higher and was 80 mg/L. In addition, the activity of PSII and the energy connection between its units increased in plants, which increased the efficiency of light energy conversion and the photosynthesis productivity index[97].

The addition of graphene oxide into the soil where *Aloe vera* plants were grown under conditions of long-term observation (4 months) increased the photosynthetic activity of leaves, their growth and the content of protein and amino acids at a stable concentration of the main biologically active compound aloin. An increase in electrolyte leakage and malondialdehyde content in root cells was also noted, but these changes were accompanied by unchanged activity of antioxidant enzymes in the root, which, according to the authors, is not related to the stress-induced effect of graphene oxide, but to the effect of growth stimulation[98].

It is noted that graphene at high concentrations (1000 mg/ml), on the contrary, inhibits the growth and photosynthetic processes of rapeseed (*Brassica napus L*.). At the same time, different forms of graphene are placed in terms of toxicity to photosynthesis processes in the following order: graphene oxide > reduced graphene oxide > amine-functionalized graphene. The reduced graphene oxide caused a negative effect on the photosynthesis process due to a decrease in the activity of the Rubisco enzyme and the content of chlorophyll *a*, and it also has a negative effect on nitrogen metabolism due to the inhibition of the transmembrane sulfate transporter. Graphene oxide changes the structure of chloroplasts, having a toxic effect on genes involved in the formation and maintenance of the structure of chloroplast membranes, the functioning of photosystems, photosynthetic electron transport and F-type ATPase, and inhibits the Rubisco enzyme. At the same time, amine-functionalized graphene did not show any toxic effects[99].

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[96] Malekzadeh M. R., Roosta H. R., Kalaji H. M. GO nanoparticles mitigate the negative effects of salt and alkalinity stress by enhancing gas exchange and photosynthetic efficiency of strawberry plants. *Sci Rep*. 2023. Vol. 13. DOI: 10.1038/s41598-023-35725-0

[97] Zhou Z., Li J., Li C., Guo Q., Hou X., Zhao C., Wang Y., Chen C., Wang Q. ffects of Graphene Oxide on the Growth and Photosynthesis of the Emergent Plant Iris pseudacorus. *Plants*. 2023. Vol. 12 (9). DOI: 10.3390/plants12091738.

[98] Zhang X., Cao H., Zhao J., Wang H., Xing B., Chen Z., Li X., Zhang J. Graphene oxide exhibited positive effects on the growth of Aloe vera L. *Physiology and Molecular Biology of Plants*. 2021. Vol. 27. P. 815–824. DOI: 10.1007/s12298-021-00979-3

[99] Xiao X., Wang X., Liu L., Chen C., Sha A., Li J. Effects of three graphene-based materials on the growth and photosynthesis of Brassica napus L. *Ecotoxicology and environmental safety*. 2022. Vol. 234. DOI: 10.1016/j.ecoenv.2022.113383

Another form of graphene, namely sulfonated graphene (SG), at a concentration of 50 mg/L induced a hormesis effect on the height of corn stalks, and also promoted the scavenging of ROS, reducing oxidative stress, increasing the content of soluble protein, reducing the content of intracellular calcium and cell death in roots. At a high concentration of 500 mg/L of the SG derivative, on the contrary, stimulation of the ROS production in roots, a decrease in the content of free protein in leaves, an increase in the activity of antioxidant enzymes and the concentration of intracellular Ca^{2+}, electrolyte leakage and cell death in the roots, as well as the amount of malondialdehyde in roots and leaves were observed[100].

Also was confirmed the stimulating effect of graphene on the development of the roots of corn seedlings. Graphene treatment has been shown to express certain transcription factor genes, auxin-responsive genes, and genes related to gibberellins, jasmonates, salicylic acid, brassinosteroids, and strigolactone[101].

Complex effect of graphene oxide and bacteria *Rhizobium sp*. E20-8 reduces drought stress effects on maize germination realized through osmotic and antioxidant properties of graphene and mitigation of nanoparticle effects on plant biochemical parameters by *Rhizobium sp*. E20-8[102].

It was found that priming of radish seeds with carbon nanoparticles under salinity conditions improves its germination, increases the antioxidant capacity of seeds due to the accumulation of such antioxidant metabolites as polyphenols, flavonoids, polyamines, anthocyanins, and proline[103].

Thus, it was shown that carbon nanoparticles of various forms have the ability to reduce the impact of stress factors on the plant organism, which is realized through various biochemical and regulatory pathways.

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[100] Ren W., Chang H., Teng Y. Sulfonated graphene-induced hormesis is mediated through oxidative stress in the roots of maize seedlings. *Sci Total Environ.* 2016. Vol. 572. P. 926–934. DOI: 10.1016/j.scitotenv.2016.07.214

[101] Chen Z., Zhao J., Song J., Han S., Du Y., Qiao Y., Liu Z., Qiao J., .Li W., Li J., Wang H., Xing B., Pan Q. Influence of graphene on the multiple metabolic pathways of Zea mays roots based on transcriptome analysis. *PloS one.* 2021. Vol. 16, № 1. DOI: 10.1371/journal.pone.0244856

[102] Lopes T., Cruz C., Cardoso P., Pinto R., Marques P. A. A. P., Figueira E. A. Multifactorial Approach to Untangle Graphene Oxide (GO) Nanosheets Effects on Plants: Plant Growth-Promoting Bacteria Inoculation, Bacterial Survival, and Drought. *Nanomaterials* (Basel). 2021. Vol. 11, № 3. DOI: 10.3390/nano11030771

[103] Halawani R. F., AbdElgawad H., Aloufi F. A., Balkhyour M. A., Zrig A., Hassan A. H. Synergistic effect of carbon nanoparticles with mild salinity for improving chemical composition and antioxidant activities of radish sprouts. *Frontiers in Plant Science*. 2023. Vol. 14. DOI: 10.3389/fpls.2023.1158031

CONCLUSIONS

A wide variety of carbon nanoparticles (CNPs) such as fullerene C_{60}, graphene, graphene oxide, single- and multi-walled nanotubes are characterized by nanoscale, chemical stability, hydrophobicity and biological activity which opens great prospects for their application in agriculture. In particular, CNPs as regulators of the physiological state, stress resistance, growth and productivity of higher plants in the cultivation, production and processing of agricultural products, as well as nanoplatforms for the delivery of mineral and organic fertilizers.

It is known that the biological action of substances depends on the structure, size, shape, surface charge, concentration, conditions and routes of administration into the nutrient medium. An important component that determines the biological effects of any substance is usually the study of the toxic properties of compounds. As toxic effects are accompanied by changes in the physiological and biochemical state of plants and lead to negative effects on the organism.

Therefore, it is proposed to use non-toxic or low-toxic carbon compounds to regulate stress resistance mechanisms in plants. The practical use of various carbon nanoparticles to protect plants from the effects of environmental stressors is promising. It should be noted that for this purpose, not only long-known nanoforms of carbon are used, but also their chemically modified water-soluble derivatives, such as hydroxyl-modified fullerol, fullerenol, reduced graphene oxide, amine-functionalized and sulfonated graphene, which are mostly less toxic, have strongly expressed antioxidant properties and are more effective in realizing the final goal.

The use of various carbon nanoparticles in conditions of abiotic stress (drought, salinity, exposure to heavy metals, increased alkalinity) and biotic stress (phytophthora) with their optimal dosage significantly reduces the impact of a negative factor due to the improvement of osmotic adaptation, increased expression of the aquaporin gene and changes in the expression of many others genes, optimization of the macroelement composition, increasing the activity of antioxidant and photosynthetic enzymes. However, it should be noted that until now the mechanisms of carbon nanoparticle penetration into plant tissues during foliar treatments and when applied to the soil or substrate remain incompletely understood, the data on the safe/effective dose of nanoparticles depending on their size and zeta potential, species are mixed plants. Therefore further study of the impact of carbon nanoparticles and their practical application in agriculture is actual.

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SUMMARY

At the moment, in Ukraine and the world in general, there is an urgent problem of food security caused by hostilities in Europe, deterioration of the ecological situation and climate changes. The rapid progress of nanotechnology has led to the use of nanomaterials in various industries. Structured carbon materials due to nanosize, hydrophobicity, antioxidant, antiviral and antibacterial properties can be used as regulators of nutrition, increasing yield and stress resistance of agricultural plants to the action of biotic and abiotic environmental factors.

The phytotoxic effects of carbon nanomaterials and their use to regulate stress resistance in agricultural plants were evaluated. The elucidation of plant resistance mechanisms and estimination adaptation links to adverse growing conditions using carbon nanomaterials will allow to regulate stress tolerance and increase the productivity of agricultural plants.

Bibliography

1. Rawtani D., Gupta G., Khatri N., Rao P. K., Hussain C. M. Environmental damages due to war in Ukraine: A perspective. *Science of The Total Environment.* 2022. Vol. 850. DOI: 10.1016/j.scitotenv.2022.157932
2. Lobell D. B., Gourdji S. M. The Influence of Climate Change on Global Crop Productivity. *Plant Physiology*. 2012. Vol. 160, № 4. P. 1686–1697. DOI: 10.1104/pp.112.208298
3. Lobell D. B., Schlenker W., Costa-Roberts J. Climate trends and global crop production since 1980. *Science.* 2011. Vol. 333. P. 616–620. DOI: 10.1126/science.1204531
4. Hatfield J. L., Boote K. J., Kimball B. A., Ziska L. H., Izaurralde R. C., Ort D., Thomson A. M., Wolfe D. Climate impacts on agriculture: Implications for crop production. *Agron J.* 2011. Vol. 103. P. 351–370. doi:10.2134/agronj2010.0303
5. Kolupaev Yu. E., Karpets Yu. V. Role of signal mediators and stress hormones in regulation of plants antioxidative system. *Fiziol. rast. genet.* 2017. Vol. 49. № 6. P. 463–481. DOI: 10.15407/frg2017.06.463
6. Iqbal M. S., Singh A. K., Ansari M. I. Effect of Drought Stress on Crop Production. *Springer*. 2020. Singapore. Vol. 35. DOI: 10.1007/978-981-15-1322-0_3

7. Kumari V. V., Banerjee P., Verma V. C., Sukumaran S., Chandran M. A. S., Gopinath K. A., Venkatesh G., Yadav S. K., Singh V. K., Awasthi N. K. Plant Nutrition: An Effective Way to Alleviate Abiotic Stress in Agricultural Crops. *Int J Mol Sci.* 2022. Vol. 23, № 15. 8519. DOI: 10.3390/ijms23158519.

8. Esmaeili N., Shen G., Zhang H. Genetic manipulation for abiotic stress resistance traits in crops. *Front. Plant Sci*. 2022. Vol. 13. DOI: 10.3389/fpls.2022.1011985

9. Prylutska S. V., Burlaka A. P., Klymenko P. P., Grynyuk, I. I. Prylutskyy Y. I.,. Schütze C, Ritter U. Using water-soluble C60 fullerenes in anticancer therapy. *Cancer Nano*. 2011. Vol. 2. 105–110. DOI: 10.1007/s12645-011-0020-x

10. Rodríguez-Lozano F. J., García-Bernal D., Aznar-Cervantes S., Oñate-Sánchez R. E., Moraleda J. M. Potential of graphene for tissue engineering applications. *Transl Res*. 2015. Vol. 166, № 4. P. 399–400. DOI: 10.1016/j.trsl.2015.04.003

11. Debnath S. K., Srivastava R. Drug Delivery With Carbon-Based Nanomaterials as Versatile Nanocarriers: Progress and Prospects. *Front. Nanotechnol.* 2021. Vol. 3. DOI: 10.3389/fnano.2021.644564

12. Hu H., Ni Y. C., Mandal S. K., Montana V., Zhao N., Haddon R. C., V. Parpura. Polyethyleneimine functionalized single-walled carbon nanotubes as a substrate for neuronal growth. *J Phys Chem B.* 2005. Vol. 109. P. 4285–4289. doi: 10.1021/jp0441137

13. Qian L., Chengfei Y., Tao Ch., Changkun D., Z. Hongtian. Construction and characterization of conductive collagen/multiwalled carbon nanotube composite films for nerve tissue engineering. *AIP Advances*. 2022. Vol. 12, № 5. DOI: 10.1063/5.0090006

14. MacDonald R. A., Laurenzi B. F., Viswanathan G., Ajayan P. M., Stegemann J. P. Collagen-carbon nanotube composite materials as scaffolds in tissue engineering. *Journal of Biomedical Materials Research.* 2005. Vol. 74 A, № 3. P. 489–496. DOI: 10.1002/jbm.a.30386

15. Tripathi D. K., Gaur S., Singh S., Singh S., Pandey R., Singh V. P., Sharma N. C., Prasad S. M., Dubey N. K., Chauhan D. K. *Plant Physiology et Biochemistry.* 2016. Vol. 110, № 2. DOI: 10.1016/j.plaphy.2016.07.030.

16. Serag M. F., Kaji N., Habuchi S., Bianco A., Baba Y. Nanobiotechnology meets plant cell biology: carbon nanotubes as organelle targeting nanocarriers. *RSC Adv*. 2013. Vol. 3. 4856–4862. DOI: 10.1039/c2ra22766e.

17. Begum P, Ikhtiari R., Fugetsu B., Matsuoka M., Akasaka T., Watari F. Phytotoxicity of multi-walled carbon nanotubes assessed by selected plant species in the seedling stage. *Applied Surface Science.* 2012. Vol. 262. P. 120–124. DOI: 10.1016/j.apsusc.2012.03.028

18. Prylutska S. V., Franskevych D. V., Yemets A. I. Cellular biological and molecular genetic effects of carbon nanomaterials in plant. *Cytol Genet*. 2022. Vol. 56, № 4. P. 351–360. DOI: 10.3103/S0095452722040077

19. Wang Y., Shu Z., Wang W., Jiang X., Li D., Pan J., Li X. CsWRKY2, a novel WRKY gene from Camellia sinensis, is involved in cold and drought stress responses. *Biol. Plant.* 2016. Vol. 60. P. 443–451. DOI: 10.1007/s10535-016-0618-2

20. Galbraith D. W. Nanobiotechnology: silica breaks through in plants. *Nat Nanotechnol*. 2007. Vol. 2 (5). P. 272–273. DOI: 10.1038/nnano.2007.118.

21. Torney, F., Trewyn, B., Lin, VY. Wang K. Mesoporous silica nanoparticles deliver DNA and chemicals into plants. *Nature Nanotech*. 2007. Vol.2. P. 295–300. DOI: 10.1038/nnano.2007.108

22. Lahiani M. H., Dervishi E., Chen J., Nima Z., Gaume A., Biris A. S., Khodakovskaya M. V. Impact of carbon nanotube exposure to seeds of valuable crops. *ACS Appl Mater Interfaces*. 2013 Vol. 5 (16). P. 7965–7973. DOI: 10.1021/am402052x.

23. Bianco A., Kostarelos K., Partidos Ch. D., Prato M. Biomedical applications of functionalised carbon nanotubes. *Chemical Communications*. 2005. № 5. P. 571–577. DOI: 10.1039/B410943K

24. Cao Z., Zhou H., Kong L., Li L., Wang R., Shen W. A. Novel Mechanism Underlying Multi-walled Carbon Nanotube-Triggered Tomato Lateral Root Formation: the Involvement of Nitric Oxide. *Nanoscale Res Lett.* 2020. Vol. 15 (1). DOI: 10.1186/s11671-020-3276-4

25. Khodakovskaya M. V., De Silva K., Biris A. S., Dervishi E., Villagarcia H. Carbon nanotubes induce growth enhancement of tobacco cells. ACS nano. 2012. Vol. 6, № 3. P. 2128–2135. DOI: 10.1021/nn204643g

26. Kwak S.-Y., T. T. S. Lew, C. J. Sweeney, V. B. Koman, M. H. Wong, K. Bohmert-Tatarev, K. D. Snell, J. S. Seo, N. H. Chua, and M. S. Strano, *Nat. Nanotechnol*. **14**, No 5: 447 (2019). doi: 10.1038/s41565-019-0375-4

27. Lew T. T. S., Wong M. H., Kwak S.-Y., Sinclair R., Koman V. B., Strano M. S. Rational Design Principles for the Transport and Subcellular Distribution of Nanomaterials into Plant Protoplasts. *Small.* 2018. Vol. 14 (44). DOI:10.1002/smll.201802086

28. Giraldo J. P., Landry M. P., Faltermeier S. M., Mc Nicholas T. P., Iverson N. M., Boghossian A. A., Reuel N. F., Hilmer A. J., Sen F., Brew J. A., Strano M. S. Plant nanobionics approach to augment photosynthesis and biochemical sensing. *Nat Mater*. 2014. Vol. 13 (4): 400–408. DOI: 10.1038/nmat3890

29. Velikova V., Petrova N., Kovács L., Petrova A., Koleva D., Tsonev T., Taneva S., Petrov P., Krumova S. Single-Walled Carbon

Nanotubes Modify Leaf Micromorphology, Chloroplast Ultrastructure and Photosynthetic Activity of Pea Plants. *Int J Mol Sci*. 2021. Vol. 22 (9). DOI:10.3390/ijms22094878

30. Shen C. X., Zhang Q. F., Li J., Bi F. C., Yao N. Induction of programmed cell death in Arabidopsis and rice by single-wall carbon nanotubes. *Am J Bot*. 2010. Vol. 97 (10). P. 1602–1609. DOI: 10.3732/ajb.1000073

31. Ghasempour M., Iranbakhsh A., Ebadi M., Oraghi Ardebili Z. Multi-walled carbon nanotubes improved growth, anatomy, physiology, secondary metabolism, and callus performance in Catharanthus roseus: an in vitro study. *3 Biotech*. 2019. Vol. 9 (11). DOI:10.1007/s13205-019-1934-y

32. Martínez-Ballesta M. C., Zapata L., Chalbi N., Carvajal M. Plant nanobionics approach to augment photosynthesis and biochemical sensing. *J Nanobiotechnol.* 2016. Vol. 14. DOI: 10.1186/s12951-016-0199-4

33. Tiwari D. K., Dasgupta-Schubert N., Villaseñor Cendejas L. M., Villegas J., Carreto Montoya L., Borjas García S. E. Interfacing carbon nanotubes (CNT) with plants: enhancement of growth, water and ionic nutrient uptake in maize (Zea mays) and implications for nanoagriculture. *Appl Nanosci.* 2014. Vol. 4. 577-591. DOI: 10.1007/s13204-013-0236-7

34. Hao Y., Yu Y., Sun G., Gong X., Jiang Y., Lv G., Zhang Y., Li L., Zhao Y., Sun D., Gu W., Qian C. Single-Walled Carbon Nanotubes Modify Leaf Micromorphology, Chloroplast Ultrastructure and Photosynthetic Activity of Pea Plants. *Plants.* 2023. Vol. 12. № 8. DOI: 10.3390/plants12081604

35. Oliveira H. C., Seabra A. B., Kondak S., Adedokun O. P., Kolbert Z. Multilevel approach to plant-nanomaterial relationships: from cells to living ecosystems. *Journal of Experimental Botany*. 2023. Vol. 74, № 12. P. 3406–3424. DOI:10.1093/jxb/erad107

36. Keita K., Okafor F. C., Nyochembeng L. M., Overton A., Sripathi V. R., Odutola J. A. Plant and Microbial Growth Responses to Multi-Walled Carbon Nanotubes. *J Nanosci Curr Res*. 2018. Vol. 3. DOI: 10.4172/2572-0813.1000123

37. Miralles P., Johnson E., Church T. L., Harris A. T. Multiwalled carbon nanotubes in alfalfa and wheat: toxicology and uptake. *J. R. Soc. Interface.* 2012. Vol. 9, № 77. P. 93514–93527. DOI: 10.1098/rsif.2012.0535

38. Avanasi R., Jackson W. A., Sherwin B., Mudge J. F., Anderson T. A. C60 fullerene soil sorption, biodegradation, and plant uptake. *Environ. Sci. Technol*. 2014. Vol. 48 (5). P. 2792–2797. DOI: 10.1021/es405306w

39. Wang Ch., Zhang H., Ruan L., Chen L., Li H., Chang X.-L., Zhang X., Yang S.-T. Bioaccumulation of 13C-fullerenol nanomaterials in wheat. *Environ. Sci.: Nano.* 2016. Vol. 4 (3). 799–805. DOI: 10.1039/C5EN00276A

40. Kole C., Kole P., Randunu K. M., Choudhary P., Podila R., Ke P. C., Rao A. M., Marcus R. K. Nanobiotechnology can boost crop production and quality: first evidence from increased plant biomass, fruit yield and phytomedicine content in bitter melon (Momordica charantia). *BMC Biotechnol.* 2013. Vol. 13. DOI: 10.1186/1472-6750-13-37

41. He A., Jiang J., Ding J., Sheng G. D. Blocking effect of fullerene nanoparticles (nC60) on the plant cell structure and its phytotoxicity. *Chemosphere*. 2021. Vol. 278. DOI: 10.1016/j.chemosphere.2021.130474

42. Liang C., Xiao H., Hu Z., Zhang X., Hu J. Uptake, transportation, and accumulation of C60 fullerene and heavy metal ions (Cd, Cu, and Pb) in rice plants grown in an agricultural soil. *Environ Pollut.* 2018. Vol. 235. P. 330–338. DOI: 10.1016/j.envpol.2017.12.062

43. Guo K. R., Adeel M., Hu F., Xiao Z. Z., Wang K. X., Hao Y., Rui Y. K., Chang X. L. Absorption of Carbon-13 Labelled Fullerene (C60) on Rice Seedlings and Effect of Phytohormones on Growth. *J Nanosci Nanotechnol*. 2021. Vol. 21 (6). P. 3197–3202. DOI: 10.1166/jnn.2021.19307

44. Gao J., Wang Y., Folta K. M., Krishna V., Bai W., Indeglia P., Georgieva A., Nakamura H., Koopman B., Moudgil B. Polyhydroxy fullerenes (fullerols or fullerenols): beneficial effects on growth and lifespan in diverse biological models. *PLoS One*. 2011. Vol. 6 (5). DOI: 10.1371/journal.pone.0019976.

45. Chen L., Wang C., Li H., Qu X., Yang S., Chang X. Bioaccumulation and Toxicity of 13C-Skeleton Labeled Graphene Oxide in Wheat. *Environmental science & technology*. 2017. Vol. 51, № 17. P. 10146–10153. DOI: 10.1021/acs.est.7b00822

46. Huang C., Xia T., Niu J., Yang Y., Lin S., Wang X., Yang G., Mao L., Xing B. Transformation of 14 C-Labeled Graphene to 14 CO_2 in the Shoots of a Rice Plant. *Angewandte Chemie*. 2018. Vol. 57, № 31. P. 9759–9763. DOI: 10.1002/anie.201805099

47. Chen L., Yang S., Liu Y., Mo M., Guan X., Huang L., Sun C., Yang S., Chang X. Toxicity of graphene oxide to naked oats (Avena sativa L.) in hydroponic and soil cultures. *RSC Advances*. 2018. Vol. 8 (28). P. 15336–15343. DOI: 10.1039/c8ra01753k.

48. Zhao S., Zhu X., Mou M., Wang Z., Duo L. Assessment of graphene oxide toxicity on the growth and nutrient levels of white clover (Trifolium repens L.). *Ecotoxicology and environmental safety*. 2022. Vol. 234. DOI: 10.1016/j.ecoenv.2022.113399

49. Zhou Z., Li J., Li C., Guo Q., Hou X., Zhao C., Wang Y., Chen C., Wang Q. ffects of Graphene Oxide on the Growth and Photosynthesis of the Emergent Plant *Iris pseudacorus*. *Plants*. 2023. Vol. 12 (9). DOI: 10.3390/plants12091738.

50. Xiao X., Wang X., Liu L., Chen C., Sha A., Li J. Effects of three graphene-based materials on the growth and photosynthesis of *Brassica napus L. Ecotoxicology and environmental safety*. 2022. Vol. 234. DOI: 10.1016/j.ecoenv.2022.113383

51. Begum P., Ikhtiari R., Fugetsu B. Graphene phytotoxicity in the seedling stage of cabbage, tomato, red spinach, and lettuce. *Carbon*. 2011. Vol. 49. P. 3907–3919. DOI: 10.1016/j.carbon.2011.05.029

52. Guo X., Zhao J., Wang R., Zhang H., Xing B., Naeem M., Yao T., Li R., Xu R. F., Zhang Z., Wu J. Effects of graphene oxide on tomato growth in different stages. *PPB*. 2021. Vol. 162. P. 447–455. DOI: 10.1016/ j.plaphy.2021.03.013

53. Ren W., Chang H., Teng Y. Sulfonated graphene-induced hormesis is mediated through oxidative stress in the roots of maize seedlings. *Sci Total Environ*. 2016. Vol. 572. P. 926–934. DOI: 10.1016/j.scitotenv.2016.07.214

54. Chen Z., Zhao J., Song J., Han S., Du Y., Qiao Y., Liu Z., Qiao J., Li W., Li J., Wang H., Xing B., Pan Q. Influence of graphene on the multiple metabolic pathways of Zea mays roots based on transcriptome analysis. *PloS one*. 2021. Vol. 16, № 1. DOI: 10.1371/journal.pone.0244856

55. Malekzadeh M. R., Roosta H. R., Kalaji H. M. GO nanoparticles mitigate the negative effects of salt and alkalinity stress by enhancing gas exchange and photosynthetic efficiency of strawberry plants. *Sci Rep*. 2023. Vol. 13. DOI: 10.1038/s41598-023-35725-0

56. Zhang X., Cao H., Zhao J., Wang H., Xing B., Chen Z., Li X., Zhang J. Graphene oxide exhibited positive effects on the growth of *Aloe vera L. Physiology and Molecular Biology of Plants*. 2021. Vol. 27. P. 815–824. DOI: 10.1007/s12298-021-00979-3

57. Zhao S., Wang Q., Zhao Y., Rui Q., Wang D. Toxicity and translocation of graphene oxide in Arabidopsis thaliana. *Environ Toxicol Pharmacol*. 2015. Vol. 39 (1). 145–156. DOI: 10.1016/j.etap.2014.11.014

58. Dong S., Jing X., Lin S., Lu K., Li W., Lu J., Li M., Gao S., Lu S., Zhou D., Chen C., Xing B., Mao L. Root Hair Apex is the Key Site for Symplastic Delivery of Graphene into Plants. *Environ Sci Technol*. 2022. Vol. 56, № 17. P. 12179–12189. DOI: 10.1021/acs.est.2c01926.

59. Wang S., Liu Y., Wang X., Xiang H., Kong D., Wei N., Guo W., Sun H. Effects of concentration-dependent graphene on maize seedling development and soil nutrients *Sci Rep*. 2023. Vol. 13 (1). DOI: 10.1038/s41598-023-29725-3A.

60. Mirza F. S., Aftab Z. E., Ali M. D., Aftab A., Anjum T., Rafiq H., Li G. Green synthesis and application of GO nanoparticles to augment growth parameters and yield in mungbean (*Vigna radiata L.*). *Front Plant Sci*. 2022. Vol. 13. DOI: 10.3389/fpls.2022.1040037

61. Liu S., Wei H., Li Z., Li S., Yan H., He Y., Tian Z. Effects of Graphene on Germination and Seedling Morphology in Rice. *J Nanosci Nanotechnol*. 2015. Vol. 15 (4). DOI: 10.1166/jnn.2015.9254

62. Zhou Q., Hu X. Systemic Stress and Recovery Patterns of Rice Roots in Response to Graphene Oxide Nanosheets. *Environ Sci Technol*. 2017. Vol. 51 (4). DOI: 10.1021/acs.est.6b05591

63. Du J., Wang T., Zhou Q., Hu X., Wu J., Li G., Li G., Hou F., Wu Y. Graphene oxide enters the rice roots and disturbs the endophytic bacterial communities. *Ecotoxicol Environ Saf.* 2020. Vol.192. DOI: 10.1016/j.ecoenv.2020.110304

64. Bradshaw D., Hardwick K. Evolution and stress – genotypic and phenotypic components. *Biological Journal of the Linnean Society*. 1989. Vol. 37, № 1–2. P. 137–155. DOI:10.1111/j.1095-8312.1989.tb02099.x

65. Chen Z., Soltis D. E. Evolution of environmental stress responses in plants. *Plant, Cell and Environment.* 2020. Vol. 43. P. 2827–2831. DOI: 10.1111/pce.13922

66. Cramer G. R., Urano K., Delrot S., Pezzotti M., Shinozaki K. Effects of abiotic stress on plants: a systems biology perspective. *BMC Plant Biol.* 2011. Vol. 11. DOI: 10.1186/1471-2229-11-163

67. Fahad S., Bajwa A. A., Nazir U., Anjum S. A., Farooq A., Zohaib A., Sadia S., Nasim W., Adkins S., Saud S., Ihsan M. Z., Alharby H., Wu C., Wang D., Huang J. Crop Production under Drought and Heat Stress: Plant Responses and Management Options. *Front. Plant Sci*. 2017. Vol. 8. DOI: 10.3389/fpls.2017.01147

68. Aguirre-Becerra H., Feregrino-Pérez A. A., Esquivel K., Perez-Garcia C. E., Vazquez-Hernandez M. C., Mariana-Alvarado A. Nanomaterials as an alternative to increase plant resistance to abiotic stresses. *Front. Plant Sci.* 2022. Vol. 13. DOI: 10.3389/fpls.2022.1023636

69. Arruda S. C., Silva A. L., Galazzi R. M., Azevedo R. A., Arruda M. A. Nanoparticles applied to plant science: a review. *Talanta*. 2015. Vol. 131. P. 693–705. DOI: 10.1016/j.talanta.2014.08.050

70. Wohlmuth J., Tekielska D., Čechová J., Baránek M. Interaction of the Nanoparticles and Plants in Selective Growth Stages-Usual Effects and Resulting Impact on Usage Perspectives. *Plants*. 2022. Vol. 11 (18). DOI: 10.3390/plants11182405

71. Samadi S., Saharkhiz M. J., Azizi M., Samiei L., Karami A., Ghorbanpour M. Single-wall carbon nano tubes (SWCNTs) penetrate *Thymus daenensis* Celak. plant cells and increase secondary metabolite accumulation in vitro. *Industrial Crops and Products*. 2021. Vol. 165. DOI: 10.1016/j.indcrop.2021.113424

72. Hatami M., Hadian J., Ghorbanpour M. Mechanisms underlying toxicity and stimulatory role of single-walled carbon nanotubes in Hyoscyamus niger during drought stress simulated by polyethylene glycol. *J Hazard Mater*. 2017. Vol. 324 (Pt B). P. 306–320. DOI: 10.1016/ j.jhazmat.2016.10.064

73. González-García Y., Cadenas-Pliego G., Alpuche-Solís Á. G., Cabrera R. I., Juárez-Maldonado A. Carbon Nanotubes Decrease the Negative Impact of Alternaria solani in Tomato Crop. *Nanomaterials (Basel, Switzerland)*. 2021. Vol. 11 (5). DOI:10.3390/nano11051080

74. Subotić A., Jevremović S., Milošević S., Trifunović-Momčilov M., Đurić M., Koruga Đ. Physiological Response, Oxidative Stress Assessment and Aquaporin Genes Expression of Cherry Tomato (*Solanum lycopersicum L.*) Exposed to Hyper-Harmonized Fullerene Water Complex. *Plants (Basel)*. 2022. Vol. 11. № 21. DOI: 10.3390/plants11212810.

75. Ozfidan-Konakci C., Alp F. N., Arikan B., Balci M., Parmaksizoglu Z., Yildiztugay E., Cavusoglu H. The effects of fullerene on photosynthetic apparatus, chloroplast-encoded gene expression, and nitrogen assimilation in Zea mays under cobalt stress. *Physiol Plant*. 2022. Vol. 174, № 3. DOI: 10.1111/ppl.13720

76. Shafiq F., Iqbal M., Ali M., Ashraf M. A. Fullerenol regulates oxidative stress and tissue ionic homeostasis in spring wheat to improve net-primary productivity under salt-stress. *Ecotoxicol Environ Saf*. 2021. Vol. 211. DOI: 10.1016/j.ecoenv.2021.111901

77. Borišev M., Borišev I., Župunski M., Arsenov D., Pajević S., Ćurčić Ž., Vasin J., Djordjevic A. Drought Impact Is Alleviated in Sugar Beets (Beta vulgaris L.) by Foliar Application of Fullerenol Nanoparticles. *PLoS One*. 2016. Vol. 11. DOI: 10.1371/journal.pone.0166248

78. Farooq M., Wahid A., Kobayashi N., Fujita D., Basra S. M.A. Plant drought stress: effects, mechanisms and management. *Agronomy for Sustainable Development*. 2009. Vol. 29. P. 185–212. DOI: 10.1051/ agro:2008021

79. Xiong J. L., Li J., Wang H. C., Zhang C. L., Naeem M. S. Fullerol improves seed germination, biomass accumulation, photosynthesis and antioxidant system in *Brassica napus L*. under water stress. *Plant Physiol Biochem*. 2018. Vol. 129. P. 130–140. DOI: 10.1016/j.plaphy.2018.05.026

80. Kong H., Meng X., Akram N. A., Zhu F., Hu J., Zhang Z. Seed Priming with Fullerol Improves Seed Germination, Seedling Growth and Antioxidant Enzyme System of Two Winter Wheat Cultivars under Drought Stress. *Plants (Basel)*. 2023. Vol. 12 (6). DOI: 10.3390/plants12061417

81. Xiong J. L., Ma N. Transcriptomic and Metabolomic Analyses Reveal That Fullerol Improves Drought Tolerance in *Brassica napus L. Int J Mol Sci*. 2022. Vol. 23. DOI: 10.3390/ijms232315304

82. Lopes T., Cruz C., Cardoso P., Pinto R., Marques P. A. A. P., Figueira E. A. Multifactorial Approach to Untangle Graphene Oxide (GO) Nanosheets Effects on Plants: Plant Growth-Promoting Bacteria Inoculation, Bacterial Survival, and Drought. *Nanomaterials (Basel)*. 2021. Vol. 11. № 3. DOI: 10.3390/nano11030771

83. Halawani R. F., AbdElgawad H., Aloufi F. A., Balkhyour M. A., Zrig A., Hassan A. H. Synergistic effect of carbon nanoparticles with mild salinity for improving chemical composition and antioxidant activities of radish sprouts. *Frontiers in Plant Science*. 2023. Vol. 14. DOI: 10.3389/fpls.2023.1158031

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