DOI 10.31489/2021BMG4/78-84

UDC 620.3

A.T. Serikbai[1*], A.M. Aitkulov[1], A.A. Zeinidenov[1], W. Pusz[2]

[1]*Karagandy University of the name of academician E.A. Buketov, Kazakhstan;*
[2]*Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland*
**Corresponding author: arailym_serikbai@mail.ru*

Influence of zinc nanoparticles on the development of sprouts of *Avena sativa* and *Pisum sativum* plants

The research aim is to study the effect of zinc nanoparticles on morphological parameters of sprouts of monocotyledonous and dicotyledonous plants (*Avena sativa, Pisum sativum*) during its accumulation in the environment. In laboratorial conditions of the experiment, it was found peculiar features of various concentrations of nanoparticles. It was specified the multidirectional effect of zinc macro- and nanoparticles onto growth rate, green weight of both aboveground and underground parts, as well as species related effect. Authors of the article identified concentrations of macro- and nanoparticles trigger permanent biological response on the experimental plants. A stable stimulating effect of zinc nanoparticles on all indicators of growth and development of pea seedlings at the concentration of 20 mg per 100 ml was revealed. A similar effect was found in oat seedlings which were exposed to zinc nanoparticles at the concentration of 5 mg per 100 ml. The effects of zinc macro- and nano-particles on plants were manifested differently.

Keywords: nanoparticles, macroparticles, zinc, plants, *Avena sativa, Pisum sativum*, morphological parameters.

Introduction

There is a limited number of studies by the Kazakh authors related to the study of the physical and chemical properties of metal nanoparticles [1–3], while the physiological properties and the toxic effect of these xenobiotics on living organisms have not been studied to all intents and purposes.

In the Russian journals and overseas scientific publications, there are a number of works devoted to assessing the effect of metal nanoparticles on both plants and animal organisms. It is revealed that nanoparticles have both positive and negative effects on these organisms. The positive effect of nanoparticles (NPs) of zinc and its compounds is found in mammals and birds [4], which is associated with changes in the parameters of the intestinal barrier and antioxidant protection. By conducting a research on rodents and fish using in vitro and in vivo methods and, Rajput V.D. et al. (2018) [5] proves the importance of developing the metal nanoparticles' toxicity criteria. Similar conclusions are reached by Chen et al. (2016) [6], who emphasize the need to study the toxic effect of zinc NPs on terrestrial and aquatic animals, and to revise the levels of these pollutants in natural conditions, especially if a synergistic toxic effect is possible with a complex of pollutants.

A number of studies have shown both positive and negative effects of metal nanoparticles and their oxides on the growth, productivity and physiology of plants, including agricultural crops [7–10]. Some authors demonstrate how safe the environmental pollution by nanoparticles [11–12], while other researchers emphasize on some significant risks of contact of plant organisms with nanosized particles [13–16].

In this regard, the issues related to the effect of metal nanoparticles on biological objects remain an urgent and practically significant.

Experimental

For the experiments, the suspensions of Zn particles of various concentrations 5, 10, 20, 200 mg per 100 ml of distilled water were utilized. The particle sizes were 80–100 nm (nanoparticles) and 500–1,000 nm (macroparticles) [17–18].

Agricultural monocotyledonous crops — cultivated oat (*Pisum sativum*, "Irtysh 15" variety) and dicotyledonous plants — green pea (*Avena sativa*, "Sugary pod" variety) were selected as typical test organisms. The growth and weight parameters of seedlings were studied [19–21].

The suspensions of NPs in various concentrations and in a volume of 10 ml were applied to filter paper in Petri dishes. The plant seeds were sown there in an amount of 15 pieces per one dish. In 14 days, the roots of the seedlings were placed on filter paper ribbons, which were rolled up into a loose roll and immersed in

plastic cups with a volume of 150 ml distilled water (Fig. 1). The plant weight and their growth were measured in 28 days after the start of the experiment.

The work was carried out at the Research Center for Biotechnology and Eco-Monitoring. The nanoparticles of zinc were synthesized at the Research Center for Ion Plasma Technologies and Modern Instrumentation of Karagandy University of the name of academician E.A. Buketov.

A B

Figure 1. The test plants in plastic cups (A) and in Petri dishes (B)

Both plant species were cultivated in climatic chamber BINDER, temperature +24 ºC, lighting 14 hours.

Results and Discussion

Observations over biological development showed that macro- and nanoparticles of zinc had different effects on the seedlings of the cultures under the experiment.

The macroparticles of zinc had a depressing effect on oat seedlings in all experimental groups, which led to a decrease (Tab. 1) in the root length compared to the control values by 75.1 and 24.7 %, 7.6 %, 25.6 %, respectively.

Table 1

Growth and weight parameters of *Avena sativa* seedlings

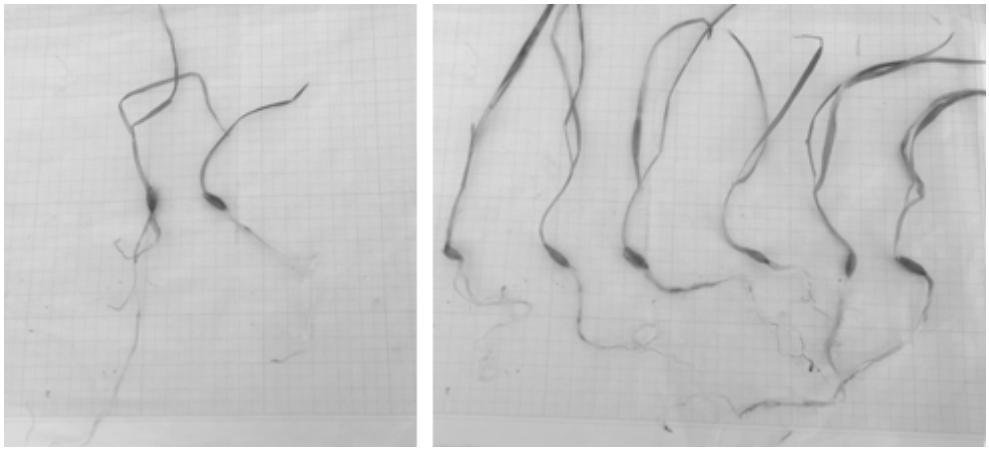
Concentration, mg/100 ml	Length of main root, cm	Aboveground part length, cm	Bio mass, g	
			Underground part	Aboveground part
Control	11.46 ± 2.96	10.6 ± 1.43	0.15 ± 0.06	0.07 ± 0.02
Macroparticles				
5	2.85 ± 1.56	4.5 ± 0.79	0.07± 0.01	0.03 ± 0.01
10	8.63 ± 2.64	11.0± 0.89	0.07± 0.03	0,06 ± 0.04
20	10.8 ± 2.4	9.2 ± 1.7	0.15± 0.06	0.07 ± 0.02
200	8.53 ± 2.34	10.72 ± 1.17	0.14± 0.03	0.06 ± 0.02
Nanoparticles				
5	15.2 ± 3.26	13.1 ± 1.9	0.14 ± 0.04	0.1 ± 0.02
10	13.0 ± 2.75	12.42 ± 2.78	0.16 ± 0.03	0.09 ± 0.02
20	8.13 ± 1.35	11.47 ± 2.21	0.16 ± 0.03	0.08 ± 0.02
200	12.28 ± 0.74	11.48 ± 1.76	0.15 ± 0.04	0.08 ± 0.01

When roots of seedlings treated with nanoparticles at the concentrations of 5, 10 and 200 mg, an increase in this indicator was noted by 32.6 %, 13.4 % and 7.1 %, respectively. At the same time, at the concentration of 20 mg/ml, the length of main root decreased by 29.1 % compared to the control values.

Measurement of the length of the aerial part of oat seedlings demonstrated that treatment with zinc macroparticles in some concentrations has a depressing effect on their growth parameters, and nanosized particles in all concentrations have a stimulating effect (Fig. 2). Compared with the control values, when treated with macroparticles at the concentrations of 5, 20 mg, the sizes of leaves and stems decreased by 57.6 % and 13.2,%, respectively. At the same time, at the concentration of metal particulates of 10 mg, an

increase in this indicator by 3.7 % was noted. The treatment of oat seeds with nanoparticles at all concentrations led to an increase in the length of the aerial part compared to the control values by 23.6 %, 17.2 %, 8.2 %, 8.3 %, respectively.

The wet weight of the underground oats organs, treated with zinc nanoparticles, had similar values for the experimental and control groups, while the weight of the roots of seedlings, treated with suspensions of macroparticles of 5 and 10 mg, was lower than the control values. A similar picture was observed by studying the parameters of the mass of the aerial part of seedlings.



A B

Figure 2. Appearance of seedlings of seed oats in the control (A) and against the background of zinc nanoparticles (B)

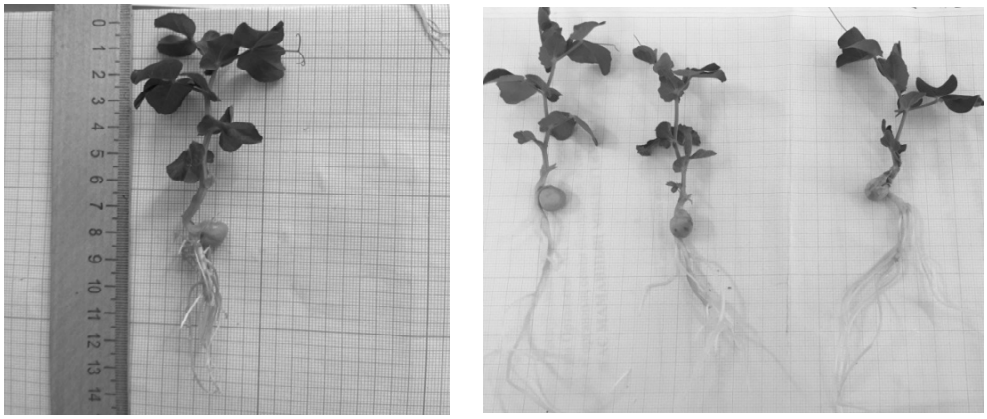
When studying the effect of zinc particles on the green pea, it was found that high values of all morphological parameters of the aboveground and underground parts of seedlings were recorded under exposure to zinc nanoparticles at the concentration of 20 mg (Tab. 2, Fig. 3). The nanoparticles at the concentration of 5 mg caused a significant increase in the mass of the aboveground part of the plants and the length of the underground part, with a decrease in its mass, compared with the control values.

Table 2

Growth and weight parameters of *Pisum sativum* seedlings

Concentration, mg / 100 ml	Length of main root, cm	Aboveground part length, cm	Bio mass, g	
			Underground part	Aboveground part
Control	7.17 ± 2.83	4.01 ± 1.71	0.53 ± 0.04	0.16 ± 0.09
Macroparticles				
5	8.05 ± 3.16	6.13 ± 2.52	0.39 ± 0.09	0.26 ± 0.12
10	5.42 ± 3.12	2.33 ± 1.13	0.55 ± 0.1	0.1 ± 0.06
20	4.94 ± 1.7	6.43 ± 2.34	0.5 ± 0.14	0.29 ± 0.11
200	4.44 ± 1.59	5.21 ± 3.87	0.52 ± 0.1	0.18 ± 0.07
Nanoparticles				
5	13.2 ± 2.42	4.69 ± 0.95	0.37 ± 0.07	0.22 ± 0.05
10	4.69 ± 1.38	3.61± 1.67	0.53 ± 0.13	0.12 ± 0.06
20	8.39 ± 3.25	5.13.± 2.96	0.59 ± 0.1	0.2 ± 0.11
200	7.92 ± 2.8	5.2 ± 1.13	0.49 ± 0.05	0.24 ± 0.06

An increase in the concentration of macroparticles led to a decrease in the length of the underground part. Thus, at the concentration of 5 mg, the root length increased by 10.9 %, while at a concentration of 10, 20, and 200 mg/ml, the root length significantly decreased in comparison with the control values by 32.2 %, 45.1 % and 61.5 %, accordingly.



A B

Figure 3. The internal view of pea seedlings after treatment with nanoparticles (A) and macroparticles (B)

In the experimental groups of those plants treated with nanoparticles, the root length exceeded the control values by 84.1 %, 17.0 %, and 10.5 % when treated at the concentration of 5, 20, and 200 mg, respectively. The shortest root length was observed in the variant with the concentration of 10 mg, where the length decreased by 34.6 %.

The study of the length of the aerial part of the green pea illustrated that the treatment with macroparticles and nanoparticles at the concentration of 10 mg has a depressing effect on the morphological parameters of both leaves and stems. Compared with the control values, the sizes of leaves and stems decreased by 41.9 % and 10.0 %, respectively. When treated with macroparticles at the concentrations of 5 and 20 mg, the leaf and stem length indicators were higher than the control indicators by 37.3 % and 38.7 %, respectively.

The treatment with nanoparticles at the concentration of 5, 20 and 200 mg has a beneficial effect on the plants. The lengths of the plants' sprouts were 16.9 %, 27.9 %, and 29.7 %, respectively.

A decrease in the weight of the root was observed upon treatment with macroparticles at the concentration of 5 and 20, 200 mg, which corresponds to 26.4 %, 5.7 %, and 1.9 %. At the same time, at the concentration of 10 mg of macroparticles, a slight increase in this indicator by 3.8 % was observed.

When treated with nanoparticles at the concentration of 10 mg, no change in the root wet weight was observed in comparison with the control values. At the same time, at the concentration of nanoparticles of 20 mg, an increase in this indicator by 11.3 % was noted. A decrease in the root weight was observed upon treatment with nanoparticles at the concentration of 5 and 200 mg by 30.2 % and 2.4 %, respectively.

The wet weight of the aerial part of the green pea treated with both macroparticles and zinc nanoparticles was higher than the control values, except for the case at the concentration of 10 mg, which caused a decrease in the indicator by 37.5 % when exposed to macroparticles and by 25 % when exposed to nanoparticles.

The study of the length of the underground part of Pisum sativum when treated with macroparticles showed that, in addition to those varieties treated at the concentration of 5 mg, an increase in the growth rate was observed. Whereas concentrations of 10, 20, 200 mg inhibited the root growth. When treated at the concentration of 5, 20 mg, an excess of the control values for the wet weight of aboveground organs was observed.

Conclusions

It can be concluded that the experiment with the treatment of oat and green pea by zinc water suspensions showed the dependence of the biological reaction of these plants on the particle size and the metal concentration.

In general, the suspensions of zinc nanoparticles caused a stimulating effect on oat seedlings, while the effect of macroparticles led to a decrease in a number of morphological parameters. The maximum values of the morphological parameters of oat seedlings were revealed when exposed to zinc nanoparticles at the concentration of 5 mg per 100 ml. The opposite effect manifested in the suppression of the growth of both

underground and aboveground parts of the plants was caused by the exposure to macroparticles at the concentration of 5 mg per 100 ml.

The treatment of green pea with zinc macroparticles mainly caused the stimulation of the length and mass of the plant sprouts, while most of the morphological parameters remained unchanged or decreased relative to the control values. The impact of suspensions of nanoparticles on the green pea caused an increase in the mass of the aerial part. Other morphological indicators showed a multidirectional nature of the reaction to the effect of nanoparticles. It should be noted that there is a stable stimulating effect of zinc nanoparticles on all indicators of growth and development of the green pea's seedlings at the concentration of 20 mg per 100 ml and the opposite effect of zinc macroparticles at the concentration of 10 mg per 100 ml.

To elucidate what mechanisms can be the basis for the reaction of the plants to such action of macro- and nanoparticles of zinc, an extensive study of the morphological structure of aboveground and underground organs, as well as changes in biochemical processes in them, is further required.

References

1 Алтынбекова Д.Т. Синтез наночастиц металлов и их сплавов с использованием сверхкритических флюидов / Д.Т. Алтынбекова, Б.К. Масалимова // Вестн. Казах.-Британ. техн. ун-та. — 2020. — № 3 (54). — С. 12–21.

2 Бақара А.Е. Пламенная экстракция металлических наночастиц и их использование во взрывчатых веществах: дис. … магистра наук / А.Е. Бақара. — Алматы: Казах. нац. ун-т, 2013. — 125 с.

3 Нанотехнологии для окружающей среды и медицины: обзор. — Алматы: Аналитическое экологическое агентство «Green women», 2018. — 45 с.

4 Zhang J. Baseline-Free Damage Diagnostic Imaging Approach Relying on the Extraction of Converted Modes of Ultrasonic Guided Waves / J. Zhang, H. Xu, K. Zhou, Zh. Yang, K. Liu, Y. Zheng, S. Ma, Zh. Wu // Journal of Aerospace Engineering. — 2021. — Vol. 34, No. 6. — P. 24–32. https://doi.org/10.1061/(ASCE)AS.1943–5525–0001319

5 Rajput V.D. Effects of zinc-oxide nanoparticles on soil, plants, animals and soil organisms: A review / V.D. Rajput, T. Minkina, A. Behal, S.N. Sushkova, S.S. Mandzhieva, R. Singh, A.V Gorovtsov, V. Tsitsuashvili, O.W. Purvis, K. Ghazaryan, H.S. Movsesyan // Environmental Nanotechnology, Monitoring & Management. — 2018. — Vol. 9. — P. 76–78. https://doi.org/10.1016/j.enmm.2017.12.006

6 Chen A. Evaluation of the effect of time on the distribution of zinc oxide nanoparticles in tissues of rats and mice: a systematic review / A. Chen, L. Shao, X. Feng, S. An, Y. Zhang, T. Sun // IET Nanobiotechnol. — 2016. — Vol. 10, No. 3. — P. 97–106. https://doi.org/10.1049/ien-nbt.2015.0006

7 Du W. TiO_2 and ZnO nanoparticles negatively affect wheat growth and soil enzyme activities in agricultural soil / W. Du, Y. Sun, R. Ji, J. Zhu, J. Wu, H. Guo // Journal of Environmental Monitoring. — 2011. — Vol. 13. — P. 822–828. https://doi.org/10.1039/c0em00611d

8 Arruda S.C.C. Nanoparticles applied to plant science: a review / S. C.C. Arruda, A. Silva, R.M. Galazzi, R.A. Azevedo, M.A.Z. Arruda // Talanta. — 2015. — Vol. 131. — P. 693–705. https://doi.org/10.1016/j.talanta.2014.08.050

9 Ruttkay-Nedecky B. Nanoparticles based on essential metals and their phytotoxicity / B. Ruttkay-Nedecky, O. Krystofova, L. Nejdl, V. Adam // Journal of Nanobiotechnology. — 2017. — Vol. 15. — P. 33–35. https://doi.org/10.1186/s12951-017-0268-3

10 Чурилов Г.И. Влияние нанопорошков железа, меди, кобальта в системе «почва–растение» / Г.И. Чурилов // Вестн. Оренбург. гос. ун-та. — 2009. — № 12 (106). — С. 148–151.

11 Rizwan M. Effect of metal and metal oxide nanoparticles on growth and physiology of globally important food crops: a critical review / M. Rizwan, S. Ali, M.F. Qayyum, Y.S. Ok, M. Adrees, M. Ibrahim, M.Z. Rehman, M. Farid, F. Abbas // Journal of Hazardous Materials. — 2017. — Vol. 322. — P. 2–16. https://doi.org/10.1016/j.jhazmat.201605.061

12 Kim S. Alteration of phytotoxicity and oxidant stress potential by metal oxide nanoparticles in *Cucumis sativus* / S. Kim, S. Lee, I. Lee // Water Air and Soil Pollution. — 2012. — Vol. 223. — P. 2799–2806. https://doi.org/10.1007/s11270-011-1067-3

13 Dimkpa C.Ü. CuO and ZnO nanoparticles: phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat / C.Ü. Dimkpa, J.E. McLean, D.E. Latta, E. Manangon, D.W. Britt, W.P. Johnson, M.I. Boyanov, A.J. Anderson // Journal of Nanoparticle Research. — 2012. — Vol. 14. — P. 1125–1129. https://doi.org/10.1007/s11051-012-1125-9

14 Shaw A.K. Nano-CuO stress induced modulation of antioxidative defense and photosynthetic performance of Syrian barley (*Hordeum vulgare* L.) / A.K. Shaw, S. Ghosh, H.M. Kalaji, K. Bosa, M. Brestic, M. Zivcak, Z. Hossain // Environmental and Experimental Botany. — 2014. — Vol. 102. — P. 10237–10247. https://doi.org/10.1016/j.envexpbot.2014.02.016

15 Da Costa M.V.J. Effect of copper oxide nanoparticles on growth, morphology, photosynthesis, and antioxidant response in *Oryza sativa* / M.V.J. Da Costa, P.K. Sharma // Photosynthetica. — 2016. — Vol. 54, Issue 1. — P. 110–119. https://doi.org/10.1007/s11099–015–0167–5

16 Faizan M. Zinc oxide nanoparticle-mediated changes in photosynthetic efficiency and antioxidant system of tomato plants / M. Faizan, A. Faraz, M. Yusuf, S.T. Khan, S. Hayat // Photosynthetica. — 2018. — Vol. 56, No. 2. — P. 678–686. https://doi.org/10.1007/s11099-017-0717-0

17 Астафурова Т.П. Особенности концентрационной зависимости развития проростков пшеницы в водных дисперсных системах наночастиц платины / Т.П. Астафурова, Ю.Н. Моргалев, В.Г. Боровикова, А.П. Зотикова, Г.С. Верхотурова, Т.А. Зайцева, В.М. Постовалова, Т.А. Моргалева // Физиология растений и генетика. — 2013. — Т. 45, № 6. — С. 544–549.

18 Егорова Е.М. Наночастицы металлов в растворах: биохимический синтез и применение / Е.М. Егорова // Нанотехника. — 2004. — № 1. — С. 15–26.

19 Моргалев Ю.Н. Методические основы выбора лабораторных тест-объектов для оценки экотоксичности наночастиц и наноматериалов / Ю.Н. Моргалев, Н.С. Хоч, Т.Г. Моргалева, Г.Е. Дунаевский, А.П. Зотикова, С.Ю. Моргалев, И.А. Гостева, И.В. Лущаева, Т.П. Астафурова. — Томск: Изд-во ТПУ, 2010. — 133 с.

20 ГОСТ 12038–84. Межгосударственный стандарт «Семена сельскохозяйственных культур. Методы определения всхожести».

21 Буренина А.А. Оценка воздействия высокодисперсных материалов на структурно-функциональные параметры растений на разных этапах развития: дис. … канд. биол. наук / А.А. Буренина. — Томск, 2019. — 125 с.

А.Т. Серікбай, А.М. Айткулов, А.А. Зейниденов, В. Пуш

Мырыш нанобөлшектерінің *Avena sativa* және *Pisum sativum* өсімдіктерінің өскіндерінің дамуына әсері

Зерттеудің мақсаты — қоршаған ортада мырыш нанобөлшектерінің жинақталуы кезінде дара және қосжарнақты өсімдіктердің (Avena sativa, Pisum sativum) өскіндерінің, олардың морфологиялық параметрлеріне әсерін зерттеу. Мырыштың әр түрлі макро- және нанобөлшектерінің өсімдіктердің өсу қарқынына, жоғарыдан да, төменнен де ылғалды салмаққа жан-жақты әсері ететіндігі анықталды. Авторлардың пайымдауынша эксперименттік жұмыстағы макро- және нанобөлшектердің концентрациясы өсімдіктерде тұрақты түрде биологиялық жауап тудыратыны байқалған. Бұршақ өскіндерінің өсуі мен дамуының барлық көрсеткіштеріне мырыш нанобөлшектерінің 100 мл 20 мг концентрациядағы әсері тұрақты түрде белсенді әсер ететіндігі анықталды. Осындай нәтижеде мырыш нанобөлшектерінің 100 мл-де 5 мг концентрацияда сұлы өскіндеріне әсер ететіндігі де зерттелді. Мырыштың макро- және нанобөлшектерінің өсімдіктерге әсері әр түрлі көрінген.

Кілт сөздер: нанобөлшектер, макробөлшектер, мырыш, өсімдіктер, *Avena sativa, Pisum sativum*, морфологиялық көрсеткіштер.

А.Т. Серикбай, А.М. Айткулов, А.А. Зейниденов, В. Пуш

Влияние наночастиц цинка на развитие проростков растений *Avena sativa* и *Pisum sativum*

Цель исследования — изучить влияние наночастиц цинка на морфологические параметры проростков одно- и двудольных растений (*Avena sativa, Pisum sativum*) при его накоплении в окружающей среде. Установлено разнонаправленное влияние макро- и наночастиц цинка на скорость роста, сырую массу как сверху, так и снизу, а также влияние видов. Авторами отмечено, что концентрации макро- и наночастиц вызывают постоянный биологический ответ у растений, участвующих в эксперименте. Выявлено стойкое стимулирующее действие наночастиц цинка на все показатели роста и развития проростков гороха в концентрации 20 мг на 100 мл. Аналогичный эффект был обнаружен у проростков овса, подвергнутых воздействию наночастиц цинка, в концентрации 5 мг на 100 мл. Влияние макро- и наночастиц цинка на растения проявлялось по-разному.

Ключевые слова: наночастицы, макрочастицы, цинк, растения, *Avena sativa, Pisum sativum*, морфологические показатели.

References

1 Altynbekova, D.T., & Masalimova, B.K. (2020). Sintez nanochastits metallov i ikh splavov s ispolzovaniem sverkhkriticheskikh fliuidov [Synthesis of metal nanoparticles and their alloys using supercritical fluids]. *Vestnik Kazakhstansko-Britanskogo tekhnicheskogo universiteta — Bulletin of Kazakh-British University, 3 (54),* 12–21 [in Russian].

2 Bakara, A.E. (2018). Plamennaia ekstraktsiia metallicheskikh nanochastits i ikh ispolzovanie vo vzryvchatykh veshchestvakh [Flame extraction of metal nanoparticles and their use in explosives]. *Master's degree thesis*. Almaty: Kazakh National University [in Russian].

3 (2018). *Nanotekhnologii dlia okruzhaiushchei sredy i meditsiny: obzor [Nanotechnology for Environment and Medicine: Review]*. Almaty: Analytical ecological agency «Green women» [in Russian].

4 Zhang, J., Xu, H., Zhou, K., Yang, Zh., Liu, K., & Zheng, Y., et al. (2021). Baseline-Free Damage Diagnostic Imaging Approach Relying on the Extraction of Converted Modes of Ultrasonic Guided Waves. *Journal of Aerospace Engineering, 34 (6),* 24–32. https://doi.org/10.1061/(ASCE)AS.1943–5525–0001319

5 Rajput, V.D. Minkina, T., Behal, A., Sushkova, S.N., Mandzhieva, S.S., & Singh, R., et al. (2018). Effects of zinc-oxide nanoparticles on soil, plants, animals and soil organisms: A review. *Environmental Nanotechnology, Monitoring & Management, 9,* 76–78. https://doi.org/10.1016/j.enmm.2017.12.006

6 Chen, A., Feng, X., Sun, T., Zhang, Y., An, Sh., & Shao, L. (2016). Evaluation of the effect of time on the distribution of zinc oxide nanoparticles in tissues of rats and mice: a systematic review. *IET Nanobiotechnol., 10 (3),* 97–106. https://doi.org/10.1049/ien-nbt.2015.0006

7 Du, W. Sun, Y., Ji, R., Zhu, J., Wu, J., & Guo, H. (2011). TiO_2 and ZnO nanoparticles negatively affect wheat growth and soil enzyme activities in agricultural soil. *Journal of Environmental Monitoring, 13, 822–828.* https://doi.org/10.1039/c0em00611d

8 Arruda S.C.C., Silva, A., Galazzi, R.M., Azevedo, R.A., & Arruda, M.A.Z. (2015). Nanoparticles applied to plant science: a review. *Talanta, 131,* 693–705. https://doi.org/10.1016/j.talanta.2014.08.050

9 Ruttkay-Nedecky, B. Krystofova, O., Nejdl, L., & Adam, V. (2017). Nanoparticles based on essential metals and their phytotoxicity. *Journal of Nanobiotechnology, 15,* 33–35. https://doi.org/10.1186/s12951-017-0268-3

10 Churilov, G.I. (2009). Vliianie nanoporoshkov zheleza, medi, kobalta v sisteme «pochva–rastenie» [Influence of nanopowders of iron, copper, cobalt in the soil-plant system]. *Vestnik Orenburgskogo gosudarstvennogo universiteta — Bulletin of Orenburg State University, 12 (106),* 148–151 [in Russian].

11 Rizwan, M., Ali, S., Qayyum, M. F., Ok, Y. S., Adrees, M., Ibrahim, M., Rehman, M. Z., Farid, M., & Abbas, F. (2017). Effect of metal and metal oxide nanoparticles on growth and physiology of globally important food crops: a critical review. *Journal of Hazardous Materials, 322,* 2–16. https://doi.org/10.1016/j.jhazmat.201605.061

12 Kim, S., Lee, S., & Lee, I. (2012). Alteration of phytotoxicity and oxidant stress potential by metal oxide nanoparticles in *Cucumis sativus. Water Air and Soil Pollution, 223,* 2799–2806. https://doi.org/10.1007/s11270-011-1067-3

13 Dimkpa, C.Ü., McLean, J.E., Latta, D.E., Manangon, E., Britt, D.W., & Johnson, W. P., et al. (2012). CuO and ZnO nanoparticles: phytotoxicity, metal speciation, and induction of oxidative stress in sand-grown wheat. *Journal of Nanoparticle Research, 14,* 1125–1129. https://doi.org/10.1007/s11051-012-1125-9

14 Shaw, A.K., Ghosh, S., Kalaji, H.M., Bosa, K., Brestic, M., Zivcak, M., & Hossain, Z. (2014). Nano-CuO stress induced modulation of antioxidative defense and photosynthetic performance of Syrian barley (*Hordeum vulgare* L.). *Environmental and Experimental Botany, 102*, 10237–10247. https://doi.org/10.1016/j.envexpbot.2014.02.016

15 Da Costa, M.V.J., & Sharma, P.K. (2016). Effect of copper oxide nanoparticles on growth, morphology, photosynthesis, and antioxidant response in *Oryza sativa*. *Photosynthetica, 54, 1,* 110–119. https://doi.org/10.1007/s11099-015-0167-5

16 Faizan, M., Faraz, A., Yusuf, M., Khan, S. T., & Hayat, S. (2018). Zinc oxide nanoparticle-mediated changes in photosynthetic efficiency and antioxidant system of tomato plants. *Photosynthetica, 56, 2,* 678–686. https://doi.org/10.1007/s11099-017-0717-0

17 Astafurova, T.P., Morgalev, Yu.N., Borovikova, V.G., Zotikova, A.P., Verhoturova, G.S., & Zajceva, T.A., et al. (2013). Osobennosti kontsentratsionnoi zavisimosti razvitiia prorostkov pshenitsy v vodnykh dispersnykh sistemakh nanochastits platiny [Features of concentration dependence of wheat seedlings development in aqueous dispersed systems of platinum nanoparticles]. *Fiziologiia rastenii i genetika — Plant physiology and genetics, 45, 6*, 544–549 [in Russian].

18 Egorova, E. M. (2004). Nanochastitsy metallov v rastvorakh: biokhimicheskii sintez i primenenie [Nanoparticles of metals in solutions: biochemical synthesis and use]. *Nanotekhnika — Nanotechnics, 1,* 15–26 [in Russian].

19 Morgalev, Yu.N., Hoch, N.S., Morgaleva, T.G., Dunaevskij, G.E., Zotikova, A.P., & Morgalev, S.Yu., et al. (2010). *Metodicheskie osnovy vybora laboratornykh test-obektov dlia otsenki ekotoksichnosti nanochastits i nanomaterialov [Methodological bases for selecting laboratory test objects for assessing the ecotoxicity of nanoparticles and nanomaterials]*. Tomsk: Tomsk Polytechnical University [in Russian].

20 (1984). *GOST 12038–84. Mezhgosudarstvennyi standart «Semena selskokhoziaistvennykh kultur. Metody opredeleniia vskhozhesti» [State Standard 12038–84. Interstate Standard "Seeds of Crops. Germination Methods"]* [in Russian].

21 Burenina, A.A. (2019). Otsenka vozdeistviia vysokodispersnykh materialov na strukturno-funktsionalnye parametry rastenii na raznykh etapakh razvitiia [Assessment of the effect of highly dispersed materials on the structural and functional parameters of plants at different stages of development]. *Candidate's thesis*. Tomsk [in Russian].