sciendo

PROCEEDINGS OF THE LATVIAN ACADEMY OF SCIENCES. Section B,
Vol. 76 (2022), No. 2 (737), pp. 204–210.

DOI: 10.2478/prolas-2022-0031

Review

NANOPARTICLES IN PLANT BIOTECHNOLOGY: ACHIEVEMENTS AND FUTURE CHALLENGES

Inese Kokina[#] and Ilona Plaksenkova

Institute of Life Science and Technologies, Daugavpils University, 13 Vienības Str., Daugavpils, LV-5401, LATVIA

[#] Corresponding author, inese.kokina@du.lv

Communicated by Isaak Rashal

Nanoparticles (NPs) are a wide class of materials, which have at least one dimension less than 100 nm. They are actively used in plant biology research due to their unique physicochemical properties. However, the large-scale application of NPs has led researchers to consider the problems, challenges, and consequences of their environmental effect. The aim of this paper is to summarise current achievements and progress of NP use in plant biotechnology and also to evaluate future implications in this field.

Keywords: *plant nanobiotechnology, plant tissue cultures, somaclonal variation, plant yield.*

INTRODUCTION

Nanobiotechnology is a biology-based, application-oriented frontier area of research that integrates nanoscience and biotechnology with an equivalent contribution (Tripathi *et al.*, 2017; Giraldo *et al.*, 2019; Shahcheraghi *et al.*, 2022) to produce various types particles at a nanoscale level with specific functions. Nanoparticles (NPs) are a wide class of materials, which have at least one dimension less than 100 nm (Khan *et al.*, 2017; Sheikholeslami *et al.*, 2020). Nanoparticles are usually classified into three groups: one-dimensional NPs, two-dimensional NPs, and three-dimensional NPs. The one-dimensional system describes thin films with size 1–100 nm or monolayers. Carbon nanotubes and Dendrimers, Quantum Dots, Fullerenes (Carbon 60), (QDs) are two- and three-dimensional NPs, respectively (Bhatia, 2016).

Great attention has been paid due to the unique physicochemical properties of NPs, which arise specifically from a higher surface to volume ratio (Gokak and Taranath, 2015; Faizan *et al*., 2018). Therefore, development of nanotechnology and industrial application of NPs has essentially increased in the last decade (Azevedo *et al*., 2017; Shah and Mraz, 2020). Moreover, the increasing release of NPs in the environment in the future is predicted (Minetto *et al*., 2016; Shahcheraghi *et al.*, 2022). NPs have received global attention due to their extensive applications in numerous fields of science, such as biomedical, physiochemical, health care, drug delivery, food and feed, environment, mechanics and other applications (Ahmed *et al*., 2016; Tortella *et al.*, 2020). On the other side, the large-scale application of NPs has led researchers to consider the problems, challenges and consequences of their environmental effect (Gottschalk *et al*., 2015; Luo *et al*., 2018). If NPs enter the soil through agricultural applications, they can accumulate in the soil in time because of their weak migration ability. As primary producers, plants have a key role as a potential pathway for the transport of NPs, and NPs can be accumulated through food chains in high trophic-level consumers, since plants contribute a significant part of the human diet, ecosystems and the environment (Yang *et al*., 2017; Ma *et al*., 2018; Kik *et al.*, 2020). In recent years, efforts of researchers in this field have been focused on the interactions between plants and NPs, and evaluation of interdisciplinary knowledge in the different fields of biosafety and practical applications (Tolaymat *et al*., 2015; Servin and White, 2016; Faizan *et al*., 2018; Shahcheraghi *et al.*, 2022). The aim of this paper was to summarise current achievements and progress of NP use in plant biotechnology and to evaluate future implications in this field as well.

EFFECTS OF NPS ON PLANTS

Positive or negative effect of NPs on plants depends on their size, shape, concentration, composition, physical and chemical properties (Ma *et al*., 2010; Fincheira *et al.*, 2020).

© Latvian Academy of Sciences
This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

Most of the studies concerning interactions between NPs and plants have been focused on the potential toxicity of NPs to plants; these studies have found both positive and negative or inconsequential effects (Table 1).

Table 1. Effects of different NPs on plants

Plants/plants parts or development stage	NPs/Size/Concentration	Interactions	References
Arabidopsis/seedlings	AgNPs/20–80 nm/ ppm	Concentration and particle size dependent phytotoxicity	Ma *et al.*, 2010
Mung bean and sorghum	AgNPs/5–25 nm/40 mg·l^{-1}	Concentration dependent-growth inhibition effect	Lee *et al.*, 2012
Radish and lettuce	AgNPs/ 1; 2.5; 5 and 10 mg·l^{-1}	Root and leaf length were not affected	Gruyer *et al.,* 2014
Cucumber	CeO2 and ZnO / 0, 400, and 800 mg/kg of soil	At 800 mg/kg treatment, CeO2 NPs reduced the yield by 31.6% the high concentration treatments resulted in the bioaccumulation of Ce and Zn in the fruit (1.27 mg of Ce and 110 mg Zn per kg dry weight)	Zhao *et al*., 2013
Soybean and maize	MWCNTs and C70 NPs	Biomass reduction around 36.5–45%	De La Torre-Roche *et al.*, 2013
Onion	ZnO NPs/ 0.0, 10,20,30 and 40 g ml^{-1}	Decreased Mitotic Index and increase in chromosomal abnormalities were observed in higher treatments. Seed germination increased in lower concentrations. Germination indices showed increased values in lower concentrations; however, these decreased significantly at higher concentrations	Shilpa and Lawre, 2014
Cucumber and wheat	Ag NPs and Ag^+	Ag NPs and Ag+ were toxic Stimulatory effects were observed on root elongation for cucumbers that were exposed to Ag NPs at concentrations below 200 mg·l$^-$, and Ag+ at concentrations below 5 mg·l$^-$	Zhang, 2014
Tomato	TiO_2 NP foliar treatment	Better growth of the plant, increase in fruit yield, and chlorophyll concentration	Raliya *et al.*, 2015
Maize	AgNPs/ 100 mg kg-1	Silver nanoparticles in soil increases maize biomass	Sillen et al., 2015
Lettuce	CeO_2 NPs/ 0, 50, 100, 1000 mg NPs per kg soil	In 100 mg·kg^{-1} significantly faster growth, but significantly increased nitrate content. Lower concentrations had no impact on plant growth.	Gui *et al.*, 2015
Common wheat Cowpea Brown mustard	Ag NPs/ 18–42 nm/ 0, 50 and 75 ppm	The optimum growth promotion and increased root nodulation were observed at 50 ppm treatment in cowpea, while improved shoot parameters were recorded at 75 ppm in *Brassica*	Pallavi *et al.*, 2016
Common wheat/plants	CuO NPs	Inhibition of growth and changed the root structure	Tang *et al.*, 2016
Red cover	TiO_2; CNTs; CeO_2	Plant biomass and AMF root colonisation were not negatively affected by NP exposure. The number of flowers was statistically lower in pots treated with 3 mg·kg($^{-1}$) MWCNT, and nitrogen fixation slightly increased at 3000 mg·kg($^{-1}$) MWCNT	Moll *et al.*, 2016
Velvet mesquite	CeO2/500 - 4000 mg·l$^-$	No visible signs of stress. The accumulation in root tissue was much higher than in the aerial part of the plant	Hernandez-Viezcas *et al.*, 2016
Eggplant	Co_3O_4-NPs	Triggered subcellular changes such as degeneration of mitochondrial cristae, abundance of peroxisomes and excessive vacuolisation	Faisal *et al.*, 2016
Eggplant	Green Synteside Ag NPs obtained from U. lactuca/ 17 mg·l$^-$	Improved eggplants growth parameters. Change in DNA profile using both RAPD and EST markers was noted	Abdellatif *et al*., 2016
Onion	Zn^{2+} Ions, ZnO-Bulk and ZnO-NPs	Significant decrease mitotic index and increase in chromosomal aberrations in a dose-dependent manner	Ahmed *et al.*, 2017
Sesame	ZnO	Bio-fabricate ZnO nanoparticles efficient in germination of *S. indicum* and can also act as antibacterial agent	Narendhran *et al.*, 2016
Barley	TiO_2 and ZnO/ 0, 5, 10, 20, 40, and 80 mg·kg^{-1}	Seed germination and root elongation are not significantly affected by types and concentrations; ZnO NPs are more toxic to barley plants than the TiO2 NPs	Doğaroğlu and Köleli, 2017
Pomelo	γ-Fe_2O_3 NPs and Fe^{3+} NPs	γ-Fe_2O_3 NPs and Fe^{3+} exposure via foliar spray had an inconsequential effect on plant growth, but γ-Fe_2O_3 NPs can reduce nutrient loss due to their strong adsorption ability. *C. maxima* plants exposed to γ-Fe_2O_3 NPs and Fe^{3+} were in iron-replete status	Hu *et al.*, 2017
Strawberry	ZnO and FeO	ZnO NPs at 150 ppm + FeO NPs at 50 ppm were found best in terms of highest growth parameters	Kumar *et al.*, 2017
Brazilian elodea	CuONPs/< 0.25 mg·l$^-$ and 1 mg·l$^-$	Doses plain 0.25 mg·l$^-$ stimilated photosynthesis; at 1 mg·l$^-$ concentration a clear suppression in photosynthesis	Rastogi *et al.*, 2017

Table 1. Continued

Plants/plants parts or development stage	NPs/Size/Concentration	Interactions	References
Barley	TiO_2/ 10% and 20% w/w TiO_2 NPs/ up to 1000? mg·l$^-$	Significant inhibition of shoot growth. Did not show any adverse effect on the shoot growth. In both experiments, (1) root growth inhibition effects became visible with increasing concentration of *n*TiO_2, (2) plants treated with *n*TiO_2 showed no change in chlorophyll *a* and *b* content, even though the plants absorbed *n*TiO_2, (3) weight of biomass treated with *n*TiO_2 was not significantly different compared to control	Kořenková *et al.*, 2017
Tomato	Ag NPs/ 0; 10; 20; 40; 80 mg·l$^-$ AgNPs	Total chlorophyll content was decreased by 80 mg/L AgNPs (69.41%), 40 mg/L AgNPs (20.89%), 20 mg·l$^-$ AgNPs (3.16%), and 10 mg·l$^-$ AgNPs (9.88%) treatments when compared to the control plants. The highest SOD and APX activity was found in the 10 mg·l$^-$ AgNPs treatment. the difference in GTS between the control and 10 mg·l$^-$ AgNPs treatment was 67.45%	Çekiç *et al.*, 2017
White mustard	Pd NPs/5 mg·l$^-$	Only for some plants – chlorosis	Kińska *et al.*, 2018
Common wheat*/root tips*	AgNPs/ 10, 20, 40 and 50?ppm in a total volume of 20?ml of dH_2O	Genotoxicity effects	Abdelsalam *et al.*, 2018
Rye	ZnO/ 31.5 nm TiO_2Ag EDDS/78.2 nm	Promoted seed germination, seedling vigour index and radicle-plumule elongation especially at concentration of 10 mg·l$^-$ nZnO-50 mg·l$^-$ nTiO_2Ag.	Doğaroğlu and Köleli, 2018
Oats	SiNPs/ 5 and 10?mM	Not toxic but leaded to better growth. The SiNPs were aggregated in roots and deposited in nano size on cell walls of leaves	Asgari *et al.*, 2018
Sesame	CdS	DNA double-strand break which can be the focal point of genome alteration and subsequent gene mutation	Das *et al.*, 2018
Radish Parvus	TiO_2 NPs; $CdCl_2$	Significant decrease of germination %, and root elongation was observed in seeds co-exposed to n-TiO_2 and $CdCl_2$ at the highest concentrations (1000 mg·l$^-$ n-TiO_2 and 250 mg·l$^-$ $CdCl_2$). The presence of n-TiO_2 did not affect the toxicity of $CdCl_2$, at least at the highest concentration (100 and 250 mg·l$^-$) in radish seeds	Manesh *et al.*, 2018
Wheat	ZnO NPs	The ZnO NPs reduced electrolyte leakage while increased SOD and POD activities in leaves of wheat	Hussain *et al.*, 2018
Onion	CuO NPs, TiO_2 NPs and Al_2O_3 NPs	CuO NPs and TiO_2 NPs significantly reduced the mitotic index (MI), whereas Al_2O_3 NPs augmented the MI. The reactive oxygen species activity of roots growing under CuO NPs, Al_2O_3 NPs, and TiO_2 NPs was significantly increased	Ahmed *et al.*, 2018
Transgenic Arabidopsis	ZnO NPs	Root exposure to ZnO-NP led to increased HR and alleviation of TGS in the aerial tissues, indicative of genotoxicity of ZnO-NP in plants	Yang *et al.*, 2018
Duckweed	ZnSe NPs	High concentration of ZnSe NPs and Zn_2+ triggered phytotoxicity. The changes in antioxidant activities confirmed higher toxicity by Zn_2+ ions in comparison with ZnSe NPs. This means that the considered ions are more hazardous to the living organisms than the nanoparticles.	Tarrahi *et al.*, 2018
Tomato	ZnO/average 35 nm/2, 4, 8, or 16 mg·l$^-$	Roots treated with 8 mg·l$^-$ for 30 min showed increased the growth, enhanced photosynthetic efficiency of plants, provided better ROS protection to plants	Faizan *et al.*, 2018
Wheat	AgNPs (25, 50, 75 and 100 mg·l$^-$)	NPs were applied to wheat plants at trifoliate stage for 3 days under heat stress; AgNPs protects wheat plants against heat stress and improve plant root length, shoot length, root number, plant fresh weight and plant dry weight in 50 and 75 mg·l$^-$ AgNPs, respectively, compared to a control	Iqbal *et al.*, 2019
Okra	ZnO NPs, 20–30nm, 5-200 mg·l$^-$	Pot culture seedlings treated for 30 days; all concentrations significantly increased seed germination, plant growth, chlorophyll, total proteins and lipids	Keerthana *et al.*, 2021
Peanuts	200 ppm nano-Ca, 200 ppm nano-B, and their combination (Ca+B)	Nanoparticle treatment was applied as two foliar sprays at the vegetative stage; both used nanoparticles significantly increased plant growth, yield, protein, oil, nitrogen, phosphate, potassium, chlorophyll level.	Abdelghany *et al.*, 2022

Based on studies performed up to the date, many important crop plants were found to have a negative response to the application of different NPs, such as decrease of mitotic index, increase of chromosomal abnormalities, change in the DNA profile and other genotoxic effects. On the other hand, improved plant growth, increase in fruit yield, chlorophyll concentration, and biomass, etc. allow concluding that cautious and sensible use of some nanoparticles can be useful in agrobiotechnology to boost agricultural production and improve food security.

NPS MECHANISM OF ENTRY INTO PLANT CELLS

A large number of studies have been performed, using different techniques, where the penetration of nanoparticles into the plant cell has been shown (Kokina *et al*., 2012; Kokina *et al*., 2017b; Tripathi *et al*., 2017; Athanassiou *et al*., 2018). The mechanism of NP transport into plant cells is still unknown in detail, but at least three ways of NPs transport into cells have been raised: (1) direct diffusion across the cell membrane, but this type of transport depends on NP parameters like size, shape, composition etc.; (2) endocytosis, when the plasma membrane creates deformations and vesicules which incorporate NPs into the cell; (3) through channels and membrane proteins, although this mechanism is quite limited due to high selectivity and small pore size (Mehrian and De Lima, 2016; Tripathi *et al*., 2017; Hubbard *et al.*, 2020). It was observed that larger NPs can penetrate into plants only through hydathodes, flower stigmas, and stomata (Chichiriccò and Poma, 2015; Hossain *et al*., 2015). In spite of the above, the extent and means of accumulation of NPs in plants, their quantification and their localisation are still unclear and further research in this area is necessary (Ruttkay-Nedecky *et al*., 2017; Hubbard *et al.*, 2020).

APPLICATION OF NPS IN PLANT BIOTECHNOLOGY

NPs are promising materials for biomolecule delivery due to their ability to cross plant cell walls without any external forces (Cunningham *et al*., 2018). In 2007, the first co-delivery of DNA and chemicals to *Nicotiana tabacum* plants via gold-capped NPs was achieved (Torney *et al*., 2007). Also, a few recent examples show promise for NPs-mediated passive delivery to plants *in vitro* and *in viv*o in *N. tabacum* protoplasts and *Arabidopsis thaliana* roots (Jiang *et al*., 2014; Burlaka *et al*., 2015). Using Dimethylaminoethyl methacrylate (DMAEM) polymer NPs in *N. tabacum* and *Ceratodon purpureus* protoplasts for yellow fluorescent protein (YFP) and GFP plasmid transportation, both transient and stable expression was reached (Finiuk *et al*., 2017). Magnetic Fe_3O_4 NPs were used for selectable marker gene transport in *Gossypium hirsutum* pollen and approximately 1% efficiency was estimated for generation of stable transgenic seeds (Zhao *et al*., 2017).

NP bombardment was shown to be a promising technology — protein-loaded Au-mesoporous silica nanoparticle was subsequently coated with plasmid DNA and successfully introduced into white onion, tobacco and wild zea tissue through particle bombardment (Martin-Ortigosa *et al*., 2012). Recently, another groups of scientists reported efficient DNA delivery and strong protein expression in *Nicotiana benthamiana*, *Eruca sativa*, *Triticum aestivum,* and *Gossypium hirsutum* leaves and *Eruca sativa* protoplasts without DNA integration in mature plants (Demirer *et al*., 2018). The main advantage of the bombardment method is delivery of DNA and effector molecules at the targeted specific site (Panpatte *et al*., 2016).

NP applications are promising in the plant cell and tissue culture field. Firstly, a widely discussed problem regarding plant tissue culture is microbial contamination, and to avoid this, sterilising agents are used, including calcium hypochlorite, ethanol, hydrogen peroxide silver nitrate, antibiotics, fungicides etc. However, the phytotoxicity many of these agents on some tissue culture developmental stages (from explants to regenerants) has been shown (Kim *et al*., 2017; Nuzhyna *et al*., 2017). A wide range of NPs such as silver, aluminum oxide, iron oxide, gold, silicon, titanium dioxide and others have been reported to significantly reduce internal and external contamination (Wang *et al*., 2017; Keshari *et al.*, 2020). At the same time, it should not be forgotten that the antimicrobial properties of NPs strongly depend from their size, shape, type and many other features.

In several studies, the effects of NPs on calli formation, embryogenesis, organogenesis and regeneration have been evaluated. For example, the presence of carbon nanoparticles in medium decreased frequency of calli formation in *Linum usitatissimum* L., and detailed histological studies showed some structural changes in calli caused by nanoparticles. Ploidy variation in calli cells significantly depended on carbon nanoparticle concentration in the medium. In calli grown on medium with carbon nanoparticles, dose-dependent DNA hypermethylation was found (Kokina *et al*., 2012). The new method of direct delivery of Au and Ag nanoparticles to flax calli and regenerant cells by vacuum deposition of metal nanolayers on powdered hormone followed by dispersal of the combined hormone-metal in medium was proposed and a significant effect of the AuNPs and AgNPs on the regeneration type of flax calli was detected (Kokina *et al*., 2013). Also, an increased embryogenesis level in banana *in vitro* cultures was observed in calluses grown on medium supplemented with ZnO NPs (Helaly *et al*., 2014). Also, a genotoxic effect of cadmium sulfide nanoparticles (CdS NPs) in rucola (*Eruca sativa* Mill.) plants was observed. Nanoparticles < 5 nm in size were found to be more toxic than larger particles at an identical mass concentration. Significant differences in cell ploidy, as well as in the mitotic index, were detected between control and treated samples. Differences in the DNA banding pattern between control samples and samples after treatment with cadmium sulfide nanoparticles were significant and detected at different places as the appearance or elimination of DNA fragments (Kokina *et al*., 2015). An-

other study showed that 25 nm Fe_3O_4 NPs pass into callus cells and induce a low level of toxicity in the callus cultures (Kokina *et al*, 2017b). Target transportation of auxin on mesoporous Au/SiO_2 nanoparticles as a method for somaclonal variation increasing in flax (*L. usitatissimum* L.) was suggested (Kokina *et al*., 2017a) and it was observed that silver and gold nanoparticles induced an increase of somaclonal variation in flax in resistance genes *Mlo* and *Pme3* (Kokina *et al*., 2017c).

The studies reported above show that nanoparticle-based techniques play a significant role in genetic research and applications in plants. Considering the results of past studies of nanotechnology application in genetic research on plants, it can be predicted that they will play a major role in addressing rising challenges in meeting human demand for food, fibre and energy (Joldersma and Liu, 2018; Mady and Kelland, 2020; Shahcheraghi *et al.*, 2022).

CONCLUSION

Undeniably, NPs have a lot to offer concerning various aspects of plant biotechnology and have demonstrated their positive role, including biomolecule delivery, genetic transformation, regulation of different stages of growth of plant tissue cultures, increasing somaclonal variation, enhancement of secondary metabolites etc. On the other hand, although NPs are already a reality with wide options of application, aspects of nanotoxicity need to be studied in detail in the future studies.

REFERENCES

Abdelghany, A. M., El-Banna, A. A., Salama, E. A., Ali, M. M., Al-Huqail, A. A., Ali, H. M., Paszt, L. S., El-Sorady, G. A., Lamlom, S. F. (2022). The individual and combined effect of nanoparticles and biofertilizers on growth, yield, and biochemical attributes of peanuts (*Arachis hypogea* L.). *Agronomy*, **12** (2), 398.

Abdellatif, K. F., Abdelfattah, R. H., El-Ansary, M. S. F. (2016). Green nanoparticles engineering on root-knot nematode infecting eggplants and their effect on plant DNA modification. *Iran J. Biotechnol*., **14** (4), 250–259.

Abdelsalam, N. R., Abdel-Megeed, A., Ali, H. M., Salem, M. Z. M., Al-Hayali, M. F. A., Elshikh, M. S. (2018). Genotoxicity effects of silver nanoparticles on wheat (*Triticum aestivum* L.) root tip cells. *Ecotoxicol. Environ. Safety*, **155**, 76–85. https://doi.org/10.1016/j.ecoenv.2018.02.069

Ahmed, B., Dwidwdi, S., Abdin, M. Z., Azam, A., Al-Shaeri, M., Khan, M. S., Saquib, Q., Al-Khedhairy, A. A., Musarrat, J. (2017). Mitochondrial and chromosomal damage induced by oxidative stress in Zn^{2+} ions, ZnO-bulk and ZnO-NPs treated *Allium cepa* roots. *Sci. Rep.,* **7**, 40685.

Ahmed, B., Shahid, M., Khan, M. S., Musarrat, J. (2018). Chromosomal aberrations, cell suppression and oxidative stress generation induced by metal oxide nanoparticles in onion (*Allium cepa*) bulb. *Metallomics*, 10, 1315**–**1327. doi: 10.1039/c8mt00093j.

Ahmed, S., Ahmad, M., Swami, B. L., Ikram, S. (2016). A review on plants extract mediated synthesis of silver nanoparticles for antimicrobial applications: A green expertise. *J. Adv. Res.,* **7**, 17–28.

Asgari, F., Majd, A., Jonoubi, P., Najafi, F. (2018). Effects of silicon nanoparticles on molecular, chemical, structural and ultrastructural characteristics of oat (*Avena sativa* L.). *Plant Physiol. Biochem.*, **127**, 152–160.

Athanassiou, C. G., Kavallieratos, N. G., Benelli, G., Losic, D., Rani, P. U., Desneux, N. (2018). Nanoparticles for pest control: current status and future perspectives. *J. Pest. Sci.*, **91**, 1–15.

Azevedo, S. L., Holz, T., Rodrigues, J., Monteiro, T., Costa, F. M., Soares, A. M. V. M., Loureiro, S. (2017). A mixture toxicity approach to predict the toxicity of Ag decorated ZnO nanomaterials. *Sci. Total Environ.,* **579**, 337–344.

Bhatia, S. (2016). Nanoparticles types, classification, characterization, fabrication methods and drug delivery applications. In: *Natural Polymer Drug Delivery Systems*. Springer, Cham, pp. 33**–**93.

Burlaka, O. M., Pirko, Y. V., Yemets, A. I., Blume, Y. B. (2015). Plant genetic transformation using carbon nanotubes for DNA delivery. *Cytol. Genet*., **49**, 349–357.

Çekiç, F. Ö., Ekinci, S., Inal, M. S., Ünal, D. (2017). Silver nanoparticles induced genotoxicity and oxidative stress in tomato plants. *Turkish J. Biol.*, **41**, 700–707.

Chichiriccò, G., Poma, A. (2015). Penetration and toxicity of nanomaterials in higher plants. *Nanomaterials*, **5**, 851–873. doi:10.3390/nano5020851.

Cunningham, F. J., Goh, N. S., Demirer, G. S., Matos, J. L., Landry, M. P. (2018). Nanoparticle-mediated delivery towards advancing plant genetic engineering. *Trends Biotechnol.,* **36** (9), 882–897.

Das, D., Datta, A. K., Kumbhakar, D. V., Ghosh, B., Pramanik, A., Gupta, S. (2018). Nanoparticle (CdS) interaction with host (*Sesamum indicum* L.): Its localization, transportation, stress induction and genotoxicity. *J. Plant Interact.,* **13** (1), 182–194.

De La Torre-Roche, R., Hawthorne, J., Deng, Y., Xing, B., Cai, W., Newman, L. A.,Wang, Q., Ma, X., Hamdi, H., White, J. C. (2013). Multiwalled carbon nanotubes and C60 fullerenes differentially impact the accumulation of weathered pesticides in four agricultural plants. *Environ. Sci. Technol*., **47** (21), 12539–12547.

Demirer, G. S., Zhang, H., Matos, J., Goh, N., Cunningham, F. J., Sung, Y., Chang, R., Aditham, A. J., Chio, L., Cho, M. J., Staskawicz, B., Landry, M. P. (2018). High aspect ratio nanomaterials enable delivery of functional genetic material without DNA integration in mature plants. *BioRxiv*. doi: https://doi.org/10.1101/179549.

Doğaroğlu, Z. G., Köleli, N. (2017). TiO_2 and ZnO nanoparticles toxicity in barley (*Hordeum vulgare* L.). *Soil Air Water*, **45** (11). https://doi.org/10.1002/clen.201700096

Doğaroğlu Z. G., Kölelia N. (2018). Co-application of EDDS and ZnO nanoparticles with TiO_2Ag nanoparticles on rye. *Int. Adv. Res. Eng. J.,* **02** (01), 009–013.

Faisal, M., Saquib, Q., Alatar, A. A., Al-Khedhairy, A. A., Ahmed, M., Ansari, S. M., Alwathnani, H. A., Dwivedi, S., Musarra, J., Praveen, S. (2016). Cobalt oxide nanoparticles aggravate DNA damage and cell death in eggplant via mitochondrial swelling and NO signaling pathway. *Biol. Res*., **49**, 20.

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**, 678–686.

Fincheira, P., Tortella, G., Duran, N., Seabra, A. B., Rubilar, O. (2020). Current applications of nanotechnology to develop plant growth inducer agents as an innovation strategy. *Crit. Rev. Biotechnol.*, **40** (1), 15–30.

Finiuk, N., Buziashvili, A., Burlaka, O., Zaichenko, A., Mitina, N., Miagkota, O., Lobachevska, O., Stoika, R., Blume, Y., Yemets, A. (2017). Investigation of novel oligoelectrolyte polymer carriers for their capacity of DNA delivery into plant cells. *Plant Cell. Tissue Organ Cult*., **131**, 27–39.

Giraldo, J. P., Wu, H., Newkirk, G. M., Kruss, S. (2019). Nanobiotechnology approaches for engineering smart plant sensors. *Nature Nanotechnol.*, **14** (6), 541–553.

Gokak, I. B., Taranath, T. C. (2015). Seed germination and growth responses of *Macrotyloma* uniflorum (Lam.) Verdc. exposed to zinc and zinc nanoparticles. *Int. J. Environ. Sci.*, **5**, 840–847.

Gottschalk, F., Lassen, C., Kjoelholt, J., Christensen, F., Nowack, B. (2015). Modeling flows and concentrations of nine engineered nanomaterials in the Danish environment. *Int. J. Environ. Res. Public Health*, **12**, 5581– 5602.

Gruyer, N., Dorais, M., Bastien, C., Dassylva, N., Triffault-Bouchet, G. (2014). Interaction between silver nanoparticles and plant growth. *ISHS Acta Horticulturae* 1037. In: *International Symposium on New Technologies for Environment Control, Energy-Saving and Crop Production in Greenhouse and Plant Factory - Greensys 2013*, pp. 795–800. doi: 10.17660/ActaHortic.2014.1037.105.

Gui, X., Zhang, Z., Liu, S., Ma, Y., Zhang, P., He, X., Li, Y., Zhang, P., Li, H., Rui, Y., Liu, L., Cao, W. (2015). Fate and phytotoxicity of CeO_2 nanoparticles on lettuce cultured in the potting soil environment. *PLoS One*, **10** (8), e0134261. doi: 10.1371/journal.pone.0134261.

Helaly, M. N., El-Metwally, M. A., El-Hoseiny, H., Omar, S. A., El-Sheery, N. I. (2014). Effect of nanoparticles on biological contamination of *in vitro* cultures and organogenic regeneration of banana. *Austral. J. Crop Sci.*, **8** (4), 612–624.

Hernandez-Viezcas, J. A., Castillo-Michel, H., Peralta-Videa, J. R., Gardea-Torresdey, J. L. (2016). Interactions between CeO_2 nanoparticles and the desert plant mesquite: A spectroscopy approach. *ACS Sustain. Chem. Eng.*, **4** (3), 1187–1192.

Hossain, Z., Mustafa, G., Komatsu, S. (2015). Plant responses to nanoparticle stress. *Int. J. Mol. Sci.*, **16**, 26644–26653. doi:10.3390/ijms161125980.

Hu, J., HuiyGuo, H., Li, J., Wang, Y., Xiao, L, Xing, B. (2017). Interaction of γ-Fe_2O_3 nanoparticles with *Citrus maxima* leaves and the corresponding physiological effects via foliar application. *J. Nanobiotechnol.*, **15**, 51.

Hubbard, J. D., Lui, A., Landry, M. P. (2020). Multiscale and multidisciplinary approach to understanding nanoparticle transport in plants. *Curr. Opin. Chem. Eng.*, **30**, 135–143. https://doi.org/10.1016/j.coche.2020.100659

Hussain, A., Ali, S., Rizwan, M., Zia Ur Rehman, M., Javed, M. R., Imran, M., Chatha, S. A. S., Nazir, R. (2018). Zinc oxide nanoparticles alter the wheat physiological response and reduce the cadmium uptake by plants. *Environ. Pollut.,* **242**, 1518–1526. doi: 10.1016/j.envpol.2018.08.036.

Iqbal, M., Raja, N. I., Mashwani, Z. U. R., Hussain, M., Ejaz, M., Yasmeen, F. (2019). Effect of silver nanoparticles on growth of wheat under heat stress. *Iranian J. Sci. Technol. Transact. A Sci.,* **43** (2), 387–395.

Jiang, L., Ding, L., He, B., Shen, J., Xu, Z., Yin, M., Zhang, X. (2014). Systemic gene silencing in plants triggered by fluorescent nanoparticle-delivered double-stranded RNA. *Nanoscale*, **6**, 9965.

Joldersma, J., Liu, Z. (2018). Plant genetics enters the nano age? Nanoparticle-mediated plant transformation. *J. Integr. Plant Biol.*, **60** (6). doi: 10.1111/jipb.12646.

Keerthana, P., Vijayakumar, S., Vidhya, E., Punitha, V. N., Nilavukkarasi, M., Praseetha, P. K. (2021). Biogenesis of ZnO nanoparticles for revolutionizing agriculture: A step towards anti-infection and growth promotion in plants. *Industr. Crops Prod.,* **170**, 113762.

Keshari, A. K., Srivastava, R., Singh, P., Yadav, V. B., Nath, G. (2020). Antioxidant and antibacterial activity of silver nanoparticles synthesized by *Cestrum nocturnum*. *J. Ayurveda Integr. Med.,* **11**(1), 37–44.

Khan, I., Saeed, K., Khan, I. (2017). Nanoparticles: Properties, applications and toxicities**.** *Arabian J. Chem.*, **12** (7), 908–931. https://doi.org/10.1016/j.arabjc.2017.05.011

Kik, K., Bukowska, B., Sicińska, P. (2020). Polystyrene nanoparticles: Sources, occurrence in the environment, distribution in tissues, accumulation and toxicity to various organisms. *Environ. Pollut.*, **262**, 114297.

Kim, D. H., Gopal, J., Sivanesan, I. (2017). Nanomaterials in plant tissue culture: The disclosed and undisclosed. *RSC Adv*., 7, 36492**–**36505. doi: 10.1039/C7RA07025J.

Kińska, K., Jiménez-Lamana, J., Kowalska, J., Krasnodębska-Ostręga, B., Szpunar, J. (2018). Study of the uptake and bioaccumulation of palladium nanoparticles by *Sinapis alba* using single particle ICP-MS. *Sci. Total Environ.,* **615**, 1078–1085.

Kokina, I., Gerbreders, V., Sledevskis, E., Bulanovs, A. (2013). Penetration of nanoparticles in flax (*Linum usitatissimum* L.) calli and regenerants. *J. Biotechnol.*, **165** (2), 127–132.

Kokina, I., Jahundoviča, I., Mickeviča, I., Jermaļonoka, M., Strautiņš, J., Popovs, S., Ogurcovs, A., Sledevskis, E., Polyakov, B., Gerbreders, V. (2017a). Target transportation of auxin on mesoporous Au/SiO_2 nanoparticles as a method for somaclonal variation increasing in flax (*L. usitatissimum* L.). *J. Nanomater.*, **2017**, 7143269. https://doi.org/10.1155/2017/7143269

Kokina, I., Jahundoviča, I., Mickeviča, I., Sledevskis, E., Ogurcovs, A., Polyakov, B., Jermaļonoka, M., Strautiņš, J., Gerbreders, V. (2015). The impact of CdS nanoparticles on ploidy and DNA damage of rucola (*Eruca sativa* Mill.) plants. *J. Nanomater.*, **2015**, 470250.

Kokina, I., Mickeviča I., Jahundoviča, I., Ogurcovs, A., Krasovska, M., Jermaļonoka, M., Mihailova, M., Tamanis, E., Gerbreders, V. (2017b). Plant explants grown on medium supplemented with Fe_3O_4 nanoparticles have a significant increase in embryogenesis. *J. Nanomater.*, **2017**, 4587147. doi: 10.1155/2017/4587147

Kokina, I., Mickeviča,I., Jermaļonoka, M., Bankovska, L., Gerbreders, V., Ogurcovs, A., Jahundoviča, I. (2017c). Case study of somaclonal variation in resistance genes *Mlo* and *Pme3* in flaxseed (*Linum usitatissimum* L.) induced by nanoparticles. *Int. J. Genom.*, **2017**, 1676874. https://doi.org/10.1155/2017/1676874

Kokina, I., Sļedevskis, E., Gerbreders, V., Grauda, D., Jermaļonoka, M., Valaine, K., Gavarane, I., Pigiņka, I., Filipovičs, M., Rashal, I. (2012). Reaction of flax (*Linum usitatissimum* L.) calli culture to supplement of medium by carbon nanoparticles. *Proc. Latvian Acad. Sci. Section B*, **66** (4/5), 200–209.

Kořenková, L., Šebesta, M., Urík, M., Kolenčík, M., Kratošová, G., Bujdoš, M., Vávra, I., Dobročka, E. (2017). Physiological response of culture media-grown barley (*Hordeum vulgare* L.) to titanium oxide nanoparticles. *Acta Agricult. Scand., Section B Soil Plant Sci.*, **67** (4), 285**–**291.

Kumar, U. J., Bahadur, V., Prasad, V. M., Mishra, S., Shukla, P. K. (2017). Effect of different concentrations of iron oxide and zinc oxide nanoparticles on growth and yield of strawberry (*Fragaria x ananassa* Duch) cv. Chandler. *Int. J. Curr. Microbiol. Appl. Sci.,* **6** (8), 2440**–**2445.

Lee, W.-M., Kwak, J. I., An, Y.-J. (2012). Effect of silver nanoparticles in crop plants *Phaseolus radiatus* and *Sorghum bicolor*: Media effect on phytotoxicity. *Chemosphere*, **86** (5), 491**–**499.

Luo, P, Roca, A., Tiede, K., Privett, K., Jiang, J., Pinkstone, J., Ma, G., Veinot, J., Boxall, A. (2018). Application of nanoparticle tracking analysis for characterising the fate of engineered nanoparticles in sediment-water systems. *J. Environ. Sci.,* **64**, 62–71.

Ma, X., Geisler-Lee, J., Deng, Y., Kolmakov, A. (2010). Interactions between engineered nanoparticles (ENPs) and plants: Phytotoxicity, uptake and accumulation. *Sci. Total Environ*., **408**, 3053–3061.

Ma, C., White, J. C., Zhao, J., Zhao, Q., Xing, B. (2018). Uptake of engineered nanoparticles by food crops: Characterization, mechanisms, and implications. *Annu. Rev. Food Sci. Technol.,* **9**, 129–53.

Mady, M. F., Kelland, M. A. (2020). Review of nanotechnology impacts on oilfield scale management. *ACS Appl. Nano Mater.,* **3** (8), 7343–7364.

Manesh, R. R., Grassi, G., Bergami, E., Marques-Santos, L. F., Faleri, C., Liberatori, G., Corsi, I. (2018). Co-exposure to titanium dioxide nanoparticles does not affect cadmium toxicity in radish seeds (*Raphanus sativus*). *Ecotoxicol. Environ. Saf.,* **148***,* 359–366. doi: 10.1016/j.ecoenv.2017.10.051.

Martin-Ortigosa, S., Valenstein, J. S., Lin, V. S. Y., Trewyn, B. G., Wang, K. (2012). Gold functionalized mesoporous silica nanoparticle mediated protein and DNA codelivery to pant cells via the biolistic method. *Adv. Funct. Mater.*, **22**, 3576–3582.

Mehrian, S. K., De Lima, R. (2016). Nanoparticles cyto and genotoxicity in plants: Mechanisms andabnormalities**.** *Environ. Nanotechnol. Monit. Manag.,* **6**, 184**–**193.

Minetto, D., Ghirardini, A.V., Libralato, G. (2016). Saltwater ecotoxicology of Ag, Au, CuO, TiO_2, ZnO and C 60 engineered nanoparticles: An overview. *Environ. Int.*, **92**, 189–201.

Moll, G., Gogos, A., Bucheli, T. D., Widmer, F., van der Heijden, M. G. (2016). Effect of nanoparticles on red clover and its symbiotic microorganisms. *J. Nanobiotechnol.*, **14**, 36. doi: 10.1186/s12951-016-0188-7.

Narendhran, S., Rajiv, P., Sivaraj, R. (2016). Toxicity of ZnO nanoparticles on germinating Sesamum indicum (Co-1) and their antibacterial activity. *Bull. Mater. Sci*., **39** (2), 415–421.

Nuzhyna, N. V., Volch, I. R., Hnatiuk, I. S., Golubenko, A. V., Bannikov, M. A. (2017). Histological peculiarities of *Triticum aestivum* L. calli cultures' morphogenesis under antibiotic Ceftriaxone influence. *Cytol. Genet.*, **51** (3),149–154.

Pallavi, Mehta, C. M., Srivastava, R., Arora, S., Sharma, A. K. (2016). Impact assessment of silver nanoparticles on plant growth and soil bacterial diversity. *3 Biotech*, **6** (2), 254.

Panpatte, D. G., Jhala, Y. K., Shelat, H. N., Vyas, R. V. (2016). Nanoparticles: The next generation technology for sustainable agriculture. In: Singh, D. P. *et al*. (eds.). *Microbial Inoculants in Sustainable Agricultural Productivity*. Springer, New Delhi, pp. 289–300. doi: 10.1007/978-81-322-2644-4_18.

Raliya, R., Nair, R., Chavalmane, S., Wang, W. N., Biswas, P. (2015). Mechanistic evaluation of translocation and physiological impact of titanium dioxide and zinc oxide nanoparticles on the tomato (*Solanum lycopersicum* L.) plant. *Metallomics,* **7**, 1584–1594. doi: 10.1039/C5MT00168D.

Rastogi, A., Zivcak, M., Sytar, O., Kalaji, H. M., He, X., Mbarki, S., Brestic, M. (2017). Impact of metal and metal oxide nanoparticles on plant: Critical review. *Frontiers Chem.,* **5**, 78. doi: 10.3389/fchem.2017.00078.

Ruttkay--Nedecky, B., Krystofova, O., Nejdl, L., Adam, V. (2017). Nanoparticles based on essential metals and their phytotoxicity. *J. Nanobiotechnol.*, **15**, 33. doi: 10.1186/s12951-017-0268-3.

Servin, A. D., White, J. C. (2016). Nanotechnology in agriculture: Next steps for understanding engineered nanoparticle exposure and risk. *NanoImpact*, **1**, 9–12.

Shah, B. R., Mraz, J. (2020). Advances in nanotechnology for sustainable aquaculture and fisheries. *Rev. Aquacult.*, **12** (2), 925–942.

Shahcheraghi, N., Golchin, H., Sadri, Z., Tabari, Y., Borhanifar, F., Makani, S. (2022). Nano-biotechnology, an applicable approach for sustainable future. *3 Biotech.*, **12** (3), 1–24.

Sheikholeslami, M., Keshteli, A. N., Babazadeh, H. (2020). Nanoparticles favorable effects on performance of thermal storage units. *J. Mol. Liquids,* **300**, 112329.

Shilpa, R., Laware, S. (2014). Effect of zinc oxide nanoparticles on cytology and seed germination in onion. *Int. J. Curr. Microbiol. App. Sci*., **3** (2), 467–473.

Sillen, W. M. A., Thijs, S., Abbamondi, G. R., Janssen, J., Weyens, N., White, J. C., Vangronsveld, J. (2015). Effects of silver nanoparticles on soil microorganisms and maize biomass are linked in the rhizosphere. *Soil Biol. Biochem.*, **91**, 14–22.

Tang, Y., He, R., Zhao, J., Nie, G., Xu, L., Xing. B. (2016). Oxidative stressinduced toxicity of CuO nanoparticles and related toxicogenomic responses in Arabidopsis thaliana. *Environ. Pollut*., **212**, 605–614.

Tarrahi, R., Khataee, A., Movafeghi, A., Rezanejad, F. (2018). Toxicity of ZnSe nanoparticles to *Lemna minor*: Evaluation of biological responses. *J. Environ Manag*., **226**, 298–307. doi: 10.1016/j.jenvman.2018.08.036.

Tolaymat, T., El Badawy, A., Sequeira, R., Genaidy, A. (2015). A system-of-systems approach as a broad and integrated paradigm for sustainable engineered nanomaterials. *Sci. Total Environ*., **511**, 595–607.

Torney, F., Trewyn, B. G., Lin, V. S., Wang, K. (2007). Mesoporous silica nanoparticles deliver DNA and chemicals into plants. *Nat. Nanotechnol*., **2**, 295–300.

Tortella, G. R., Rubilar, O., Durán, N., Diez, M. C., Martínez, M., Parada, J., Seabra, A. B. (2020). Silver nanoparticles: Toxicity in model organisms as an overview of its hazard for human health and the environment. *J. Hazard. Mater.,* **390**, 121974.

Tripathi, D. K., Singh S., Singh S., Pandey R., Singh V. P., Sharma N. C., Prasad S. M., Dubey N. K., Chauhan D. K. (2017). An overview on manufactured nanoparticles in plants: Uptake, translocation, accumulation and phytotoxicity. *Plant Physiol. Biochem.,* **110**, 2–12.

Wang, L., Hu, C., Shao, L. (2017). The anti-microbial activity of nanoparticles: Present situation and prospects for the future. *Int. J. Nanomed.*, **12**, 1227–1249. doi: 10.2147/IJN.S121956.

Yang, A., Wu, J., Deng, C., Wang, T., Bian, P. (2018). Genotoxicity of zinc oxide nanoparticles in plants demonstrated using transgenic *Arabidopsis thaliana*. *Bull. Environ. Contam. Toxicol*., **101** (4), 514**–**520. doi: 10.1007/s00128-018-2420-7.

Yang, J., Cao, W., Rui, Y. (2017). Interactions between nanoparticles and plants: Phytotoxicity and defense mechanisms. *J. Plant Interact.,* **12** (1), 158–169.

Zhang, P. (2014). Phytotoxicity of silver nanoparticles to cucumber (*Cucumis sativus*) and wheat (*Triticum aestivum*). *J. Zhejiang Univ. SCIENCE A*, **15** (8), 662**–**670.

Zhao, L., Sun ,Y., Hernandez-Viezcas, J. A., Servin, A. D., Hong, J., Niu, G., Peralta-Videa, J. R., Duarte-Gardea, M., Gardea-Torresdey, J. L. (2013). Influence of CeO_2 and ZnO nanoparticles on cucumber physiological markers and bioaccumulation of Ce and Zn: A life cycle study. *J. Agric. Food Chem.*, **61** (49), 11945–11951.

Zhao, X., Meng, Z., Wang, Y., Chen, W., Sun, C., Cui, B., Cui, J., Yu, M., Zeng, Z., Guo, S., Luo, D., Cheng, J. Q., Zhang, R., Cui, H. (2017). Pollen magnetofection for genetic modification with magnetic nanoparticles as gene carriers. *Nat. Plants*, **3**, 956–964.

Received 6 November 2018
Accepted in the final form 15 March 2022

NANODAĻIŅAS AUGU BIOTEHNOLOĢIJĀ: SASNIEGUMI UN NĀKOTNES IZAICINĀJUMI

Nanodaļiņas ir plaša materiālu klase, kuru izmērs vienā dimensijā svārstās no 1 līdz 100 nm. Nanodaļiņu unikālo fizikāli ķīmisko īpašību dēļ, tās aktīvi izmanto augu bioloģijas pētījumos. Tomēr nanodaļiņu plaša pielietošana ir likusi pētniekiem apsvērt to ietekmi uz apkārtējo vidi — izraisītās problēmas, izaicinājumus un sekas. Šī darba mērķis ir apkopot pašreizējos sasniegumus un progresu nanodaļiņu izmantošanā augu biotehnoloģijā, kā arī novērtēt nākotnes izaicinājumus šajā jomā.