Multilevel study of nickel oxide nanoparticles-associated effects in Ni hyperaccumulator *Odontarrhena lesbiaca*

Ph.D. Thesis

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1. Introduction

Nickel (Ni) is an essential micronutrient for plants, involved in various physiological and biochemical processes. Under natural conditions, soil Ni levels typically remain below 100 mg/kg. However, industrial activities—especially stainless and heat-resistant steel production—have led to a significant rise in environmental Ni concentrations, raising concerns for both ecological systems and agricultural productivity.

In recent years, nickel oxide nanoparticles (NiO NPs) have gained attention due to their unique physicochemical properties, such as high surface area, stability, and antimicrobial activity. These characteristics make them valuable in a range of industrial applications, yet their widespread use has raised questions about their environmental behavior and biological interactions, particularly with plants.

In non-accumulator plant species, excessive Ni uptake can disturb metabolic functions, inhibit enzymatic activity, and impair photosynthesis, often leading to symptoms like chlorosis, necrosis, and stunted growth. Ni exposure is also known to induce oxidative stress through the overproduction of reactive oxygen species (ROS). However, less is known about its effects on reactive nitrogen species (RNS), such as nitric oxide (NO) and *S*-nitrosoglutathione (GSNO), which play critical roles in stress signaling and regulatory pathways in plants.

Despite the toxicity of Ni to most plants, certain species, known as Ni hyperaccumulators, have evolved specialized strategies to tolerate and accumulate high levels of Ni without adverse effects. *Odontarrhena lesbiaca*, a species native to the serpentine soils of Lesbos, Greece, is one such hyperaccumulator, exhibiting ecotype-dependent variation in Ni accumulation and tolerance.

This study focuses on three ecotypes of *Odontarrhena lesbiaca* (Ampeliko, Loutra, and Olympos) to examine their physiological, structural, and molecular responses to NiO NP exposure. By analyzing Ni uptake patterns, root anatomical modifications, and nitro-oxidative stress markers, the research addresses an important gap in the understanding of hyperaccumulator interactions with engineered nanoparticles. The findings aim to contribute to the broader field of plant–nanoparticle interactions and support more sustainable environmental applications of nanomaterials.

2. Research Objectives

We aimed to examine the responses of the Ni hyperaccumulator *Odontarrhena lesbiaca* to NiO NPs. In order to be able to set up a simple, reproducible experimental system, we used seedling-stage plants grown and treated in Petri dishes. By comparing geographically distinct populations (Ampeliko, Loutra, and Olympos) growing on soils with different Ni contents, we aimed to find correlations between NiO NP effects and Ni accumulation/tolerance. Multiscale analyses of plant responses were performed at the cellular, tissue, organ, and molecular levels. Our hypothesis was that the ecotypes display unique cellular, structural, and molecular adaptations in response to NiO NP exposure, which are linked to their varying tolerance to Ni.

Therefore, we formulated the following key questions:

1) What is the extent of Ni uptake, root-to-shoot translocation and changes in element distribution of *Odontarrhena lesbiaca* seedlings in the presence of nano or bulk Ni form? Can NPs be detected in plant tissues? Can ecotype-dependent differences be identified?

2) Does the presence of NiO NPs induce modifications in root tissue structure and cell wall composition as root tissue-level protection mechanisms? Can ecotype-dependent differences be identified?

3) Do the nano and the bulk Ni form induce changes in biomass production of *Odontarrhena lesbiaca* root and shoot organs? Can ecotype-dependent differences be identified?

4) Among the molecular mechanisms of plant responses to Ni, can nitro-oxidative mechanisms be identified in *Odontarrhena lesbiaca* exposed to NiO NP? Can ecotype-dependent differences be identified?

3. Materials and Methods

Characterization of NiO NPs

NiO NPs were purchased from Sigma-Aldrich. Particle size, chemical composition, and crystallinity were analyzed using transmission electron microscopy (TEM) with electron diffraction (ED) patterns, and X-ray diffraction (XRD). Energy dispersive X-ray spectroscopy (EDS) determined elemental composition, and the specific surface area was measured by nitrogen adsorption using the BET method.

Preparation of NiO NP and bulk $NiCl_2$ solutions

NiO NPs were suspended in distilled water and sonicated to form a stable dispersion, with final concentrations of 250 mg/L or 500 mg/L. Bulk $NiCl_2$ solution was prepared similarly, adjusting pH to 5.7-5.8.

Conditions for plant growth

Seeds of *Odontarrhena lesbiaca* were provided by Prof. Dr. Panayiotis G. Dimitrakopoulos. Seeds were sterilized and grown in Petri dishes with either distilled water (control) or $NiCl_2$/NiO NP solutions. The plants were incubated in a greenhouse under controlled conditions for 5 days.

Ni concentration analysis by ICP-MS

Roots and shoots of *Odontarrhena lesbiaca* were dried, digested with nitric acid and hydrogen peroxide, and analyzed for nickel content using ICP-MS.

LIBS analysis and elemental mapping of plantlets

Laser-induced breakdown spectroscopy (LIBS) was used to analyze plantlets. Elemental maps of Ni, K, Na, Mg, and Ca were generated by scanning the plant material and processing data using specialized software.

TEM examination of root and hypocotyl sections

Root and hypocotyl samples were fixed, embedded in resin, and sectioned for TEM analysis.

Microscopic observation of root anatomy and analysis of cell wall components (lignin, suberin, pectin)

Root anatomy and cell wall components (lignin, suberin, pectin) were examined using microscopy. Staining was performed for specific components such as lignin (Auramine-O), suberin (Auramine-O), and pectin (Ruthenium Red).

Biomass production assessment

Root and shoot lengths, fresh weight (FW), and dry weight (DW) were measured to assess biomass production.

Translocation factor (TF) calculation

Ni translocation from roots to shoots was assessed using the translocation factor (TF) formula:

$$\mathrm{TF} = \frac{[\mathrm{Ni}^{2+}]\ \text{in shoot}\ (\mu\text{g/g DW})}{[\mathrm{Ni}^{2+}]\ \text{in root}\ (\mu\text{g/g DW})}$$

Assessment of reactive nitrogen species (RNS) in roots

RNS levels, including nitric oxide (NO) and peroxynitrite ($ONOO^-$), were detected using fluorescent dyes DAF-FM DA and DHR 123.

Fluorescence imaging and quantification

Fluorescence and light microscopy were used to analyze RNS, with pixel intensity quantified for fluorescence assays.

Evaluation of GSNOR activity via UV-vis absorption spectroscopy

GSNOR activity was measured by monitoring NADH oxidation in the presence of GSNO. Activity was expressed as nmol NADH consumed per minute per mg of protein.

Protein extraction and assessment of GSNOR protein levels and tyrosine nitration by western blot

Protein levels of GSNOR and tyrosine nitration were assessed by western blotting. Protein quantification was done using Bradford assay, and bands were visualized using NBT/BCIP reaction.

Statistical analysis

Data were analyzed using one-way ANOVA and Duncan's multiple range test ($P < 0.05$). Assumptions for ANOVA were verified using Hartley's Fmax and Shapiro-Wilk tests.

Summary

This study investigates the Ni hyperaccumulation mechanisms in three ecotypes of *Odontarrhena lesbiaca* (Ampeliko, Loutra, and Olympos) when exposed to Ni in NiO NPs and $NiCl_2$ forms. All ecotypes exhibited hallmark features of hyperaccumulators, including high basal Ni levels, efficient root-to-shoot translocation, and substantial shoot Ni accumulation. Distinct physiological and structural responses were observed depending on the Ni form: ionic Ni was more readily translocated to shoots, whereas NiO NPs predominantly accumulated in root tissues, likely due to cell wall immobilization.

Microscopic and biochemical analyses supported this finding, revealing electron-dense Ni deposits and pectin accumulation in the root cell walls, especially under NiO NP treatment. Each ecotype employed unique strategies to cope with Ni exposure. Ampeliko showed cortex thickening, Loutra displayed vascular adaptations, and Olympos maintained shoot growth under stress—demonstrating ecotype-specific anatomical modifications aimed at enhancing metal tolerance.

Molecular responses further indicated that NiO NP exposure triggered nitrosative signaling, with ecotype-dependent modulation of nitric oxide (NO)-related pathways. Variations in GSNOR protein levels and enzyme activity suggested complex post-translational regulation. A consistent pattern of modest protein nitration across all ecotypes emphasized their robust stress response capacity.

Overall, this study highlights the differential adaptations of *Odontarrhena lesbiaca* ecotypes to NiO NPs and $NiCl_2$, underscoring their potential for use in phytoremediation. The ecotype-specific structural and molecular mechanisms identified here provide valuable insights into plant-based strategies for managing heavy metal-contaminated environments.

Összegzés

Ez a tanulmány három *Odontarrhena lesbiaca* ökotípus (Ampeliko, Loutra és Olympos) Ni hiperakkumulációs mechanizmusait vizsgálja, amikor azok NiO NPs és $NiCl_2$ formában alkalmazott Ni többlet során. Minden ökotípus a hiperakkumulálók jellegzetes vonásait mutatta, beleértve a magas alapvető Ni szinteket, a hatékony gyökér-hajtás transzlokációt és a jelentős hajtás Ni felhalmozódást. Különböző élettani és

strukturális válaszokat figyeltünk meg a Ni forma függvényében: az ionos Ni könnyebben transzlokálódott a hajtásba, míg a NiO NP elsősorban a gyökér szövetekben halmozódott fel, valószínűleg a sejtfali megkötődés miatt.

Mikroszkópos és biokémiai eredményeink alátámasztották ezt az eredményt, hiszen elektron-denz Ni lerakódásokat és pektin felhalmozódást mutattak a gyökér sejtjeiben, különösen NiO NP kezelés hatására. Minden ökotípus egyedi stratégiákat alkalmazott a Ni-expozíció kezelésére. Ampeliko a gyökér kéreg rétegének megvastagodását mutatta, Loutra szállítószöveti módosulásokat mutatott, míg Olympos a stressz alatt is fenntartotta a hajtás növekedését, így ökotípus-specifikus anatómiai módosulásokat mutatva, amelyek a fémekkel szembeni toleranciát növelték.

Molekuláris válaszok továbbá azt mutatták, hogy a NiO NP kitettség nitrozatív jelátvitelt váltott ki, a nitrogén-oxid (NO) kapcsolt jelátviteli útvonalak ökotípus-specifikus módosulásaival. A GSNOR fehérje szintjében és enzim aktivitásában tapasztalt eltérések összetett poszttranszlációs szabályozást sugalltak. Az összes ökotípusnál megfigyelt mérsékelt fehérje nitráció és annak következetes mintázata hangsúlyozza azok erős stresszválasz kapacitását.

Összességében ez a tanulmány kiemeli *Odontarrhena lesbiaca* ökotípusainak különböző alkalmazkodásait NiO NPs és $NiCl_2$ hatására, hangsúlyozva azok potenciálját a fitoremediációban. Az itt azonosított ökotípus-specifikus strukturális és molekuláris mechanizmusok értékes betekintést nyújtanak a növényi alapú stratégiákba a nehézfémekkel szennyezett környezet kezelésére.

List of Publications

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Publications used in this dissertation

Kondak, S., Janovszky, P., Szőllősi, R., Molnár, Á., Oláh, D., Adedokun, O. P., Dimitrakopoulos, P. G., Rónavári, A., Kónya, Z., Erdei, L., Galbács, G., & Kolbert, Z. (2024). Nickel oxide nanoparticles induce cell wall modifications, root anatomical changes, and nitrosative signaling in ecotypes of Ni hyperaccumulator *Odontarrhena* *lesbiaca*. Environmental Pollution, 341, 122874. https://doi.org/10.1016/j.envpol.2023.122874.

IF: 7.6

Kondak, S., Kondak, D., Kabadayi, O., Erdei, L., Rónavári, A., Kónya, Z., Galbács, G., & Kolbert, Z. (2024). Current insights into the green synthesis, in planta characterization and phytoeffects of nickel nanoparticles and their agricultural implications. Environmental Research, 119665. https://doi.org/10.1016/j.envres.2024.119665.

IF: 7.7

Oliveira, H. C., Seabra, A. B., **Kondak, S.,** Adedokun, O. P., & Kolbert, Z. (2023). Multilevel approach of plant-nanomaterial relationship: from cells to living ecosystems. Journal of Experimental Botany, erad107. http://dx.doi.org/10.1093/jxb/erad107.

IF: 5.8

Szőllősi, R., Molnár, Á., **Kondak, S.,** & Kolbert, Z. (2020). Dual effect of nanomaterials on germination and seedling growth: Stimulation vs. phytotoxicity. Plants, 9(12), 1745. https://doi.org/10.3390/plants9121745.

IF: 4.658

Other publications

Kondak, S., Molnár, Á., Dóra, Oláh., & Kolbert, Z. (2022). The role of nitric oxide (NO) in plant responses to disturbed zinc homeostasis. Plant Stress, 100068. https://doi.org/10.1016/j.stress.2022.100068.

IF: 6.8

Oláh, D., **Kondak, S.,** Molnár, Á., Adedokun, O. P., Czékus, Z., Gémes, K., ... & Kolbert, Z. (2023). Suboptimal zinc supply affects the *S*-nitrosoglutathione reductase enzyme and nitric oxide signaling in Arabidopsis. Plant Stress, 10, 100250. https://doi.org/10.1016/j.stress.2023.100250.

IF: 6.8

Molnár, A., **Kondak, S.,** Benkő, P., Janovszky, P., Kovács, K., Szőllősi, R., Gondor, O. K., Oláh, D., Gémes, K., Galbács, G., Janda, T., & Kolbert, Z. (2022). Limited Zn supply affects nutrient distribution, carbon metabolism and causes nitro-oxidative stress in sensitive *Brassica napus*. Environmental and Experimental Botany, 202, 105032. https://doi.org/10.1016/j.envexpbot.2022.105032.

IF: 4.5

Fejes, G., Bodor, T., Szőllősi, R., **Kondak, S.,** Kutasi, K., Fotopoulos, V., & Kolbert, Z. (2025). Nitric oxide as integral element in priming-induced tolerance and plant stress memory. Journal of Experimental Botany, eraf033. https://doi.org/10.1093/jxb/eraf033.

IF: 5.8

Naneli, İ., Bagı, F., **Kondak, S.,** & Özgen, Y. (2020). Response of some rice varieties (*Oryza sativa* L.) to salinity. Journal of Agricultural Biotechnology, 1(1), 1-5.

IF: -

Cumulative IF: 49.658

Book chapters

Szőllősi, R., Molnár, Á., Oláh, D., **Kondak, S.,** & Kolbert, Z. (2022). Uptake and Metabolism of Selenium in Plants: Recent Progress and Future Perspectives. Selenium and Nano-Selenium in Environmental Stress Management and Crop Quality Improvement, 79-90. https://doi.org/10.1007/978-3-031-07063-1_5.

Szőllősi, R., Molnár, Á., Oláh, D., **Kondak, S.,** & Kolbert, Z. (2022). Selenium Toxicity and Tolerance in Plants: Recent Progress and Future Perspectives. Selenium and Nano-Selenium in Environmental Stress Management and Crop Quality Improvement, 311-324. https://doi.org/10.1007/978-3-031-07063-1_15.

Bodor, T., Fejes, G., Kondak, D., **Kondak, S.,** Szőllősi, R., & Kolbert, Z. (2025). Karrikin-Related Effects on Plant Development, Stress Tolerance, and Beyond. Strigolactones: Emerging Plant Hormones, 211-234. https://doi.org/10.1002/9781394302826.ch10.

Conference proceedings

Selahattin Kondak, Patrick Janovszky, Réka Szőllősi, Árpád Molnár, Dóra Oláh, Oluwatosin Peace Adedokun, Panayiotis G. Dimitrakopoulos, Andrea Rónavári, Zoltán Kónya, László Erdei, Gábor Galbács, Zsuzsanna Kolbert. (2024). Ecotype-Dependent Responses to Nickel Oxide Nanoparticles in Ni Hyperaccumulator *Odontarrhena lesbiaca*: Unraveling the Impact Across Cellular, Tissue, Organ, and Molecular Level. In 9th Plant Nitric oxide International Meeting (PNO9), National Institute of Plant Genome Research (NIPGR), New Delhi, India, 110067 (p.52).

Selahattin Kondak, Patrick Janovszky, Réka Szőllősi, Árpád Molnár, Dóra Oláh, Oluwatosin Peace Adedokun, Panayiotis G. Dimitrakopoulos, Andrea Rónavári, Zoltán Kónya, László Erdei, Gábor Galbács, Zsuzsanna Kolbert. (2024). Multi-Level Tolerance Mechanisms of *Odontarrhena lesbiaca* Ecotypes to Nickel Oxide Nanoparticles: Insights from Cellular Defense to Molecular Nitrosative Signaling. In Hungarian Society for Plant Biology, Society's Lecture Series for Young Plant Biologists (FIANÖVELŐ2024), University of Debrecen, Hungary.

Dóra Kondak, **Selahattin Kondak**, Oluwatosin Peace Adedokun, Tamás Bodor, Andrea Rónavári, Ágota Imre-Deák, Zsuzsanna Kolbert. (2024). Nanotechnological Interventions: Exploring the Impact of Nano-Nitric Oxide Donors in *Brassica napus*. In 9th Plant Nitric oxide International Meeting (PNO9), National Institute of Plant Genome Research (NIPGR), New Delhi, India, 110067 (p.14).

Tamás Bodor, Gábor Fejes, **Selahattin Kondak**, Réka Szőllősi, Kinga Kutasi, Zsuzsanna Kolbert. (2024). The effect of seed priming with plasma activated water on germination and RONS content of *Arabidopsis thaliana* L. In 9th Plant Nitric oxide International Meeting (PNO9), National Institute of Plant Genome Research (NIPGR), New Delhi, India, 110067 (p.57).

Gábor Fejes, Tamás Bodor, **Selahattin Kondak**, Réka Szőllősi, Kinga Kutasi, Zsuzsanna Kolbert. (2024). The effect of plasma-activated water on wheat seedling development and the levels of in planta reactive oxygen and nitrogen species. In 9th Plant Nitric oxide International Meeting (PNO9), National Institute of Plant Genome Research (NIPGR), New Delhi, India, 110067 (p.51).

Fernando A. Casian Plaza, Patrick M. Janovszky, Dávid J. Palásti, **Selahattin Kondak**, Zsuzsanna Kolbert, Gábor Galbács. (2024). Advanced laser-induced breakdown spectroscopy-based qualitative analytical methodologies for food and plant-related applications. In: Alapi, Tünde; Berkecz, Róbert; Ilisz, István (eds.) Proceedings of the 30th International Symposium on Analytical and Environmental Problems. Szeged, Hungary: Szegedi Tudományegyetem, 387 p. pp. 241-245., 5 p.

Kondak, Selahattin., Oláh, Dóra., Molnár, Árpád., Janovszky, Patrick., Dimitrakopoulos, Panayiotis G., Galbács, Gábor., & Kolbert, Zsuzsanna. (2022). Uptake and Effect of Nickel Oxide Nanoparticles on Biomass Production and Reactive Molecule Levels in Nickel-Hyperaccumulator *Odontarrhena lesbiaca* Ecotypes. In FIBOK2022 5th National Conference of Young Biotechnologists (p. 87).

Oláh, Dóra., Molnár, Árpád., **Kondak, Selahattin.,** & Kolbert, Zsuzsanna. (2022). Nitric oxide signalling in plant responses of *Arabidopsis thaliana* to limited zinc supply. In FIBOK2022 5th National Conference of Young Biotechnologists (p. 27).

Kondak, Selahattin., Oláh, Dóra., Molnár, Árpád., Dimitrakopoulos, Panayiotis G., & Kolbert, Zsuzsanna. (2021). Nickel oxide (NiO) nanoparticles uptake and effect on biomass production and reactive nitrogen species levels in Ni-hyperaccumulator *Odontarrhena lesbiaca* ecotypes. In XIII Magyar Növénybiológiai Kongresszus (p. 74).

Oláh, Dóra., Molnár, Árpád., **Kondak, Selahattin.,** & Kolbert, Zsuzsanna. (2021). A cinkhiány hatásainak vizsgálata *S*-nitrozoglutation reduktáz mutáns *Arabidopsis thaliana* gyökérrendszerében. In XIII Magyar Növénybiológiai Kongresszus (p. 80).

Kondak, Selahattin., Oláh, Dóra., Molnár, Árpád., & Kolbert, Zsuzsanna. (2021). Zinc Deficiency in *Pisum sativum*: Focusing on Reactive Oxygen, Nitrogen and Sulphur Species. In PNO2021 8th Plant Nitric Oxide International Meeting (NO82020) (p.72).

Oláh, Dóra., **Kondak, Selahattin.,** Molnár, Árpád., & Kolbert, Zsuzsanna. (2021). Zinc deficiency effect of nitric oxide (NO) signaling in *Arabidopsis thaliana*. In PNO2021 8th Plant Nitric Oxide International Meeting (NO82020) (p.76).

Kondak, Selahattin., Kumlay, Ahmet Metin, Bagı, Fatmagül., Yıldırım, Bünyamin., & Alma, Mehmet Hakkı. (2018). Biotechnological Methods for Improvement of Stevia Plant. In I. International Agricultural Science Congress, Van, Türkiye, (p.36).

Kondak, Selahattin., Rezaeieh, Kiarash Afshar Pour., Yıldırım, Bünyamin., & Gürbüz, Bilal. (2016). Ornamental Reproduction Potentials of Stevia (*Stevia rebaudiana*). (*Turkish*: Stevia (*Stevia rebaudiana* Bert.)`nın Süs Bitkisi Olma ve Üretim Potansiyeli) In VI. Ornamental Plants Congress, Antalya, Türkiye, (p. 279-282).

Kondak, Selahattin., Rezaeieh, Kiarash Afshar Pour., Yıldırım, Bünyamin., & Farshi, Sadabadi, Roya. (2016). Coneflowers (*Echinacea* spp.) capability as ornamental crops (*Turkish*: Ekinezya (*Echinacea* spp.) Süs Bitkisi Olarak Kapasitesi). In VI. Ornamental Plants Congress, Antalya, Türkiye, (p.145).

Kondak, Selahattin., Rezaeieh, Kiarash Afshar Pour., & Yıldırım, Bünyamin. (2016). Worldwide Breeding Studies On Ornamental Plants: From Past To Present (*Turkish*: Dünyada Süs Bitkileri Üzerinde Geçmişten Günümüze Islah Çalışmaları). In VI. Ornamental Plants Congress, Antalya, Türkiye, (p.125).

Kondak, Selahattin., Rezaeieh, Kiarash Afshar Pour., Yıldırım, Bünyamin., & Kumlay, Ahmet Metin. (2016). Floriculture and Ornamental Crops: An Overview to Biotechnological Advances (*Turkish*: Çiçekçilik ve Süs Bitkileri: Biyoteknolojik Gelişmelere Genel Bir Bakış). In VI. Ornamental Plants Congress, Antalya, Türkiye, (p.124).

Rezaeieh, Kiarash Afshar Pour., **Kondak, Selahattin**., Farshi, Sadabadi, Roya., & Gürbüz, Bilal. (2016). Ornamental-Medicinal Plants: Commercially Important Crops (*Turkish*: Süs - Tıbbı Bitkiler: Ticari önemli bitkiler). In VI. Ornamental Plants Congress, Antalya, Türkiye, (p.123).

Statement

As the corresponding author and co-author of the following journal publications, I hereby verify that all the findings/results presented in this thesis and the associated scientific publications have not been previously used to obtain any Ph.D. degree and will not be used for such purposes in the future.

Kondak, S., Janovszky, P., Szőllősi, R., Molnár, Á., Oláh, D., Adedokun, O. P., Dimitrakopoulos, P. G., Rónavári, A., Kónya, Z., Erdei, L., Galbács, G., & Kolbert, Z. (2024). Nickel oxide nanoparticles induce cell wall modifications, root anatomical changes, and nitrosative signaling in ecotypes of Ni hyperaccumulator *Odontarrhena* *lesbiaca*. Environmental Pollution, 341, 122874. https://doi.org/10.1016/j.envpol.2023.122874.

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Oliveira, H. C., Seabra, A. B., **Kondak, S.,** Adedokun, O. P., & Kolbert, Z. (2023). Multilevel approach of plant-nanomaterial relationship: from cells to living ecosystems. Journal of Experimental Botany, erad107. http://dx.doi.org/10.1093/jxb/erad107.

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Szőllősi, R., Molnár, Á., **Kondak, S.,** & Kolbert, Z. (2020). Dual effect of nanomaterials on germination and seedling growth: Stimulation vs. phytotoxicity. Plants, 9(12), 1745. https://doi.org/10.3390/plants9121745.

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