Review article

Current insights into the green synthesis, *in planta* characterization and phytoeffects of nickel nanoparticles and their agricultural implications

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ABSTRACT

The intensifying production and release into the environment as well as the increasing potential in agricultural applications make the relationship between plants and nickel nanoparticles (Ni NPs) a relevant and timely topic. The aim of this review is to give an overview and discuss the latest findings about the relationship of Ni NPs and plants. Ni NPs can be synthesized using phytochemicals derived from plant parts in an environmentally friendly manner. There are several ways for these nanoparticles to enter plant cells and tissues. This can be demonstrated through various imaging and chemical mapping approaches (*e.g.,* transmission electron microscopy, X-ray fluorescence spectroscopy *etc.*). NiO NPs affect plants at multiple levels, including subcellular, cellular, tissue, organ, and whole-plant levels. However, the effects of Ni NPs on plants' ecological partners (*e.g.,* rhizobiome, pollinators) remain largely unknown despite their ecotoxicological significance. The main cause of the Ni NPs-triggered damages is the reactive oxygen species imbalance as a consequence of the modulation of antioxidants. In non-tolerant plants, the toxicity of NiO NPs can be mitigated by exogenous treatments such as the application of silicon, salicylic acid, or jasmonic acid, which induce defense mechanisms whereas Ni-hypertolerant plant species possess endogenous defense systems, such as cell wall modifications and nitrosative signaling against NiO NP stress. Research highlights the role of Ni NPs in managing fungal diseases, showcasing their antifungal properties against specific pathogens. Due to the essentiality of Ni, the application of Ni NPs as nanofertilizers might be promising and has recently started to come into view.

1. Introduction

Nanotechnology pertains to the realm of science and engineering dedicated to materials having one or more dimensions of the order of 100 nm (Salata, 2004; Tailor et al., 2023). Nanomaterials (NMs) exhibit distinct differences from their bulk counterparts, not solely in size but also in morphology, chemical composition, redox behaviour, biodegradability, potential for aggregation, concentration, stability, surface attributes, solubility, and colloidal stability (Gnach et al., 2015). NMs are currently applied in a wide array of fields including biology, medicine, electronics, energy production, and environmental studies (Pakzad et al., 2019; Ahmad et al., 2022) and they carry great potential, as many of their future applications are promising. Based on structural

configuration, NMs can be categorized as carbon-based (*e.g.* fullerenes, nanotubes), organic (*e.g.* liposomes, dendrimers), inorganic (*e.g.* metal-based and metal oxides) NMs and nanocomposites (NCs, Mekuye and Abera, 2023).

Metal-based and metal oxide NMs include nickel (Ni)-containing NMs, and Ni NCs are also known. Ni is a natural component in waters and soils (Hedfi et al., 2007); and it is considered an essential ultra-micronutrient for plants; however, its role in urea metabolism is the only one that has been characterized so far. Beyond urease, Ni is a constituent of other metalloenzymes including Ni-superoxide dismutase, and acetyl-CoA synthase (Mustafa et al., 2023). Additionally, Ni has been found to stimulate the glyoxalase enzyme activity and regulate the cellular glutathione content (Fabiano et al., 2015). Ni also plays a major

role in phytoalexin synthesis (Wood and Reilly, 2007). Like most of the micronutrients, Ni exhibits dual phytoeffects depending on its concentration. Recently, NCs including five essential elements (Co, Fe, Ni, Zn, and Cu) proved to be beneficial or toxic to wheat depending on the concentration and also on the sonication time which influence particle size (Tombuloglu et al., 2024).

Supraoptimal Ni doses can disrupt metabolic processes, leading to loss of enzyme activities, decreased chlorophyll biosynthesis, and limited photosynthetic electron transport (Sreekanth et al., 2013; Genchi et al., 2020). Moreover, seed germination, biomass production and nutrient absorption are phytophysiological processes affected by excess Ni.

Due to the advancement of nanotechnology, large amounts of Ni-based NMs are produced and used in diverse areas (*e.g.* medicine, sensor development, dye absorption, Jaji et al., 2020) and this results in their introduction into soil and water, subsequently leading to interactions with plants (Chahardoli, 2023). Plants interact with Ni nanoforms (mainly nickel oxide nanoparticles, NiO NPs) suffer from various microscopic (*e.g.* chromosomal aberrations, cell cycle perturbations, Manna et al., 2022) and macroscopic (*e.g.* chlorosis, necrosis, growth inhibition, wilting, Lin and Xing, 2007; Stampoulis et al., 2009; Faisal et al., 2013; Soares et al., 2016) injuries.

The aim of this review is to discuss the available research on the relationship between Ni NPs and plants, to determine the knowledge gaps and to identify new research directions.

2. Overview of Ni nanomaterial synthesis methods: emphasis on plant-based synthesis

In today's technology landscape, chemical and physical techniques are dominant in producing NPs, but at the same time they come with significant drawbacks. Physical methods often require costly vacuum systems, while both physical and chemical approaches need strict reaction conditions, specific temperatures and pressures, high energy consumption, and flammable solvents. These methods harm the environment and living organisms by using hazardous chemicals, resulting in low yields, toxic by-products, and high energy demands (Nasrollahzadeh and Sajadi, 2015). Moreover, NPs synthesized through these routes retain harmful residues on their surfaces, reducing their compatibility and biological activity. However, in response to these challenges, there is a growing emphasis on eco-friendly nano-synthesis or bio-inspired methods as alternative approaches (Khan et al., 2021). Currently, green synthesis approaches are favourable as they contribute to waste prevention/minimization, employ safer non-toxic solvents and reduce pollution (Rónavári et al., 2017). Utilizing green methodologies for Ni nanoparticle production involves employing plant parts, extracts, or organisms, offers an alternative, straightforward and easy process as well as resulting in eco-friendly products that pose no harm to the ecosystem. Multiple research studies comparing different production techniques have indicated biogenic green Ni and its oxide-based NPs as potent antibacterial agents (Uddin et al., 2021a), highlighting their superior photocatalytic attributes (Kumar et al., 2020) as well. The synthesis of Ni NPs has frequently encountered several hurdles. Among these challenges is the complexity of reducing Ni(II) to Ni(0) at room temperature (Hossain et al., 2018). Many synthetic procedures rely on distilled water for rinsing Ni NPs, yet their susceptibility to oxidation in the air leads to the formation of Ni oxides or hydroxides such as NiO, Ni_2O_3, $Ni(OH)_2$, or NiOOH, posing significant hurdles in the synthesis process (Chen and Wu, 2000). Plant extracts, due to their cost-effectiveness, widespread availability, and plant compatibility, have gained popularity in reducing metal ions to NPs using biomolecules. These extracts, rich in bioactive phytocomponents that act as reducing and capping agents (*e.g.* enzymes, aldehydes, alcohols, flavonoids, quinines, alkaloids, terpenoids, oils, carboxylic and ascorbic acids, and phenolic compounds), enable the creation of NPs with diverse morphologies and sizes through a preferred and environmentally

friendly phytochemical synthesis. In the synthesis of Ni NPs, plant extracts from various plant parts (*e.g.* algae, leaf, flower, fruit, bark, seed, and root) are combined with aqueous solution of Ni ion, and the biosynthesis typically occurs at mild reaction conditions using room temperature and an optimal pH, either with or without stirring (Tailor et al., 2023, Fig. 1). The effective biomolecules present in plants bind to the surface of nanoparticle, preventing their aggregation and providing stability often leading to an enhanced chemical or biological activity. This synthesis approach has been successfully applied recently using extracts from various, often exotic plant species such as *Berberis balochistanica*, *Peumus boldus*, *Gymnema sylvestre*, *Opuntia ficus indica*, *etc.* (Bhoye et al., 2023; Taş et al., 2021; Uddin et al., 2021b; Gebretinsae et al., 2021) as well as the cadmium hyperaccumulator *Lactuca sativa* (Hamdan et al., 2024). However, it should be also noted that while plant-mediated procedures hold great potential; the parameters such as material selection, control of product properties and synthesis conditions, have a crucial role on the features of obtained materials. Therefore, these factors, that raise concerns regarding the implementation of large-scale application of green-synthesized nanoscale metals, require thorough research prior utilization.

3. Uptake and accumulation of Ni-containing NPs and Ni-ions derived from NPs in plants: a technical point of view

3.1. Tools of the trade

There are several analytical and imaging techniques that are applicable and has already been tested for the *in vivo* or *in vitro* detection and distribution monitoring of NPs in plants (González-Melendi et al., 2008; Yan and Chen, 2018; Sembada and Lenggoro, 2024; Zhao et al., 2022; Arruda et al., 2015). Although solution-based atomic spectroscopy, which requires prior acid digestion of the plant parts investigated can also be applied to the task in a cumbersome way, but the list of modern techniques primarily used includes scanning and transmission electron microscopies (SEM, TEM), often used in conjunction with energy dispersive X-ray fluorescence spectroscopy (EDS or EDX), fluorescence microscopy (FLM), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), single particle ICP-MS (sp-ICP-MS), laser-induced breakdown spectroscopy (LIBS), synchrotron-based X-ray fluorescence microscopy (XFM) and X-ray absorption spectroscopy (XAS). These techniques, or their "μ" variants, have micrometer-range or better spatial resolution, trace analytical sensitivity (mg·kg^{-1} range or lower) and, in some cases, chemical (elemental) selectivity to differentiate the analyte bound in a nanoparticle from the surrounding tissue. The above techniques all have a different combination of features (advantages and disadvantages), which also limit their applicability and provided information content. Please also note that smallest detectable size of NPs also depends on the composition of the particle and the quality of the element. In this section, we provide an overview of the capabilities of the techniques and describe the recent results obtained with them relevant to NiO NPs studies in plants.

SEM and TEM have excellent spatial resolution (around a few nm for SEM and below a nm for TEM), allowing for the individual detection of NPs, and generally provide morphological, size distribution and spatial distribution information. Only when they are coupled with EDX can the quality of the NPs also assessed or confirmed. This feature is limited mainly to metallic NPs. In these instances, the detectable particle size typically increases to 10–20 of nanometers or more. Metal ions cannot be detected. SEM and TEM sample preparation is not easy, usually involves ultramicrotome sectioning and metallization steps, but as a bonus, the high resolution visualization of the surrounding tissue is also obtained, although in a very small area, during the measurement (Zhao et al., 2022).

XFM studies generally use thin sectioning sample preparation similar to SEM and TEM, but on the plus side, atmospheric pressure and *in vivo* experiments are also possible. XFM has an inherent elemental
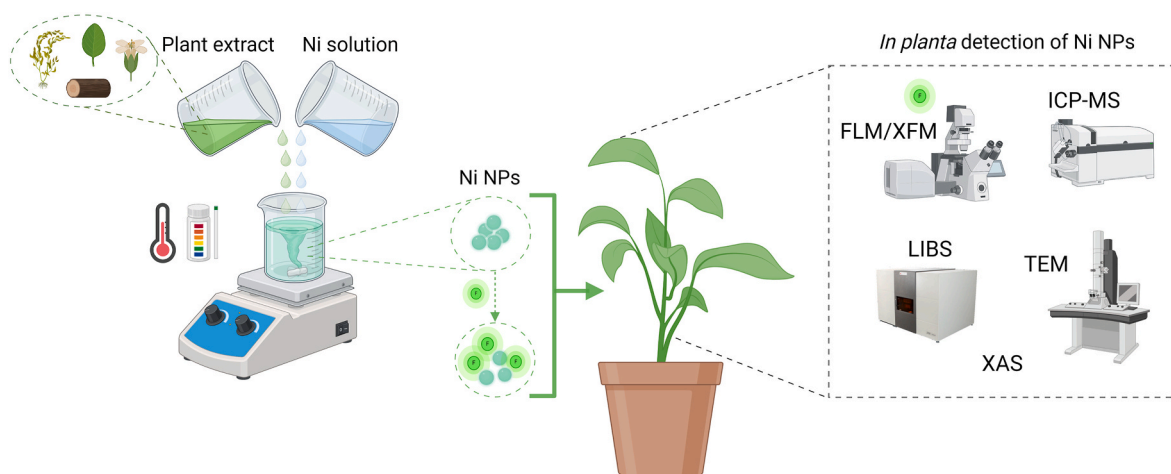
Fig. 1. Summarizing the plant-based synthesis and the methods of *in planta* detection of Ni NPs. See explanations in the text. Abbreviations: FLM/XFM, fluorescence microscopy/X-ray fluorescence microscopy; ICP-MS, inductively coupled plasma mass spectrometry; LIBS, laser induced breakdown spectroscopy; TEM transmission electron microscopy; XAS, X-ray absorption spectroscopy.

selectivity, but the detectable elements (ions or particles) are practically limited to metals too. Its spatial resolution (50 nm at best) is poorer than that of electron microscopies, but it is still adequate even for the individual detection of larger NPs. A significant drawback of XFM is that it requires a synchrotron facility thus it is less accessible than other techniques. The use of XFM to the imaging of NPs and elements in plants have been recently reviewed by Kopittke et al. (2018) and Castillo-Michel et al. (2017).

XAS studies the fine modulation features of the X-ray absorption coefficient of the sample as a function of excitation energy and also uses synchrotron radiation, similar to XFM. It provides more chemical information (*e.g.* in addition to the composition, the chemical structure is also probed) than other NP detection techniques. The spatial resolution is determined by the ca. 1–40 μm^3 interaction volume between the excitation beam and the plant sample section. The sensitivity only allows for the detection of quite large NPs (several hundred nanometers in diameter), or aggregates. Metal ions can also be detected, but only in higher concentrations. Further data on the use of XAS for NP detection in plants can be found in *e.g.* Castillo-Michel et al. (2017).

FLM is widely used for the imaging of biological samples, plants also among them. It is available in single- and two-photon configurations. Single photon excitation uses continuous-wave UV or visible light for excitation, whereas the more complicated two-photon configuration employs a pulsed (typically femtosecond) NIR laser. The spatial resolution is usually around or slightly below a micrometer, limited by the diffraction of the excitation wavelength, but the two-photon variant has a significantly higher depth resolution and better penetration into the tissue, thereby also allowing for the use of thicker sample sections. In terms of NP detection, FLM is restricted to natively luminescent/fluorescent NPs (*e.g.* quantum dots or upconverting NPs) or to NPs functionalized with a fluorophore (*e.g.* fluorescein isothiocyanate, also known as FITC, or Alexa Fluor series dyes) (Li et al., 2022). Please note that FLM usually does not have a sufficient spatial resolution to resolve smaller individual NPs, but can detect their aggregates. Metal ions can also be detected, but with a relatively low sensitivity. Plant bioimaging with FLM, including luminescent NPs, has been recently reviewed by Dong et al. (2019) and Mizuta (2021).

ICP-MS is a well-established, ultra-sensitive, element and isotope-selective analytical technique. Its absolute detection limits for metals are in the attogram range, which not only allows for the sub-ppt concentration determination of metal ions in solutions, but also for the individual detection of medium-sized (*e.g.* 20–40 nm diameter) metallic NPs, when they are dispersed in a liquid medium. The application of ICP-MS for the detection and direct analysis of NPs or metal ions in plant samples is a quite recent research direction and it is executed in one of two ways. One approach is the use of a focused laser beam to ablate the plant tissue material with a 5–50 μm spot size and determine the analyte mass originating from the NPs or metal ions studied (LA-ICP-MS). Due to the ablative character, depth resolved analysis is also possible. This approach allows for spatially resolved studies in plants. Metal ions at ppm-level concentrations and NP aggregates can be detected. Primarily concentration and compositional information can be obtained. Sample preparation is minimal, if the top couple of tens of μm layer of the tissue is targeted. Further information on the application of LA-ICP-MS to NP effects in biological samples can be found in Galazzi et al. (2020). The other approach is sp-ICP-MS, where the NPs have to enter the instrument in a highly diluted dispersion, thus sample preparation (analyte separation, matrix digestion, etc.) is needed if the particles are obtained from a biological sample. Because of this, sp-ICP-MS does not provide spatial resolution, but the statistical evaluation of particle signal spikes gives reliable information about the particle composition, size distribution, structure, dimensions, porosity and more. It can also differentiate between the ionic and particle-bound analyte signal (Galbács et al., 2021). sp-ICP-MS appears to be a very promising, versatile technique in NP detection and characterization. The first reviews on its application to biological samples, including plants have been published only very recently by Laycock et al. (2022) and Loeschner et al. (2023). Lately some studies even attempt to combine the advantages LA and sp-ICP-MS methodologies for NP analysis in biological samples (*e.g.* Seiffert et al., 2023).

LIBS elemental mapping is perhaps the tool that appeared most recently, in about the last decade, in the arsenal of NP detection studies. It uses a high intensity, pulsed laser beam to generate a microplasma in the focal spot and observes the atomic emission spectrum. Scanning the laser beam provides μm-range spatial resolution elemental maps of the plant tissue. It has trace analytical (ppm level) limits of detection towards all elements in the periodic system and is well capable of single-shot analysis. It can be used for NP uptake studies, or macro, trace element or NP distribution studies, even with depth resolution. The sensitivity typically does not allow for individual NP detection, but the aggregation of NPs can be detected. In general, LIBS is a promising tool in the elemental bioimaging of plant tissues, as it is also reflected in recent reviews exploring this approach by Modlitbová et al. (2020) and Busser et al. (2018). One unique advantage of LIBS for NP distribution studies is that it requires very little sample preparation and the measurements can also be performed in the field.

3.2. Applications to NiO NP uptake and distribution studies

Today it is understood that plants also mediate the dispersion of NPs into the environment and are contributing to their accumulation in foodstuff (De Souza-Torres et al., 2021). The interaction of NPs with plants therefore not only affect the functioning of plants, but also food quality. NPs might adhere to the plant surface, inducing physical or chemical harm, or enter the plant body through cell wall pores, depending on their size (Kurczyńska et al., 2021). The cell wall performs a size exclusion task since it can limit the entrance of NPs to those that are smaller than 20 nm. At the same time, data support that certain NMs can also increase the pore diameter or create new pores by changing the chemical composition of the cell wall (Oliveira et al., 2023). Furthermore, NPs can penetrate the root system *via* lateral root junctions, traversing the cortex and pericycle to reach the xylem (Hossain et al., 2015). Nevertheless, based on the accumulated literature data, the uptake, and *in planta* movement of NPs are influenced by various factors such as size, shape, chemical composition, types, concentration, surface charge, plant species, growth stage, and environmental exposure conditions (Singh et al., 2021).

Due to the direct and indirect importance of the above processes, diverse techniques have been developed to monitor the uptake of Ni NMs into plant organs and tissues. These techniques typically include imaging and chemical mapping approaches. For instance, Parsons et al. (2010) identified the different forms and oxidation states of Ni within the tissues of mesquite seedlings exposed to uncoated and sodium citrate-coated Ni hydroxide NPs by utilizing XAS. Ni NPs were detected in roots and shoots of uncoated NP-exposed plants, whereas a Ni (II)-organic acid type complex was found in the leaves. Additionally, in plants treated with coated NPs, Ni NPs were detectable only in roots and a Ni(II)-organic acid complex was present in shoots and leaves. Recently, the fate of Ni in soybean seeds treated with nanodisperse Ni (OH)$_2$ has been investigated by XFM and SEM (de Oliveira et al., 2022). The results suggest that independently from the type of Ni source, Ni is associated with the seed coat (especially the hilum) and is not translocated towards the emerging cotyledons, as it is transferred to the rhizosphere and finally absorbed by the radicle or the primary roots (de Oliveira et al., 2022).

TEM has proven to be a useful tool to reveal nanoparticle uptake, biodistribution and associations with cell and tissue components due to its high resolution (Malatesta, 2021). This technique allows the visualization of Ni NPs in the plant cells. Faisal et al. (2013) confirmed that NiO NPs (average size of 23 nm) reached the cytoplasm of tomato root cells. The accumulation of NiO NPs within the vacuoles of root cells was observed, suggesting successful penetration of the NPs through the seed coats and cell membranes. Additionally, increased number of peroxisomes and mitochondria in root cells of the NiO NPs treatment group, along with degenerated crystal structures and nuclear condensation were observed. Recently, the accumulation of NiO NPs (23.2 ± 8.3 nm) in the root cell walls of Ni hyperaccumulator *Odontarrhena lesbiaca* ecotypes was evidenced by TEM analysis (Kondak et al., 2024).

Ni levels were also monitored in Ni hyperaccumulator seedlings by LIBS elemental mapping. NiO NP-induced changes in the *in planta* levels of other cations such as potassium, sodium, magnesium, and calcium were also determined and compared to those induced by ionic Ni treatment. LIBS proved to be a very capable approach for the visualization of changes in the distribution of macro- and microelements in seedlings (Kondak et al., 2024).

The study by Manna et al. (2021) revealed using FLM that hydroponically administered FITC-tagged aminopropyl triethoxysilane-functionalized NiO NPs (<50 nm particle size) penetrate the epidermis in *Allium cepa* roots and move progressively from the meristematic zone into the elongation and differentiation root zones in a dose-dependent manner. The NPs penetrate individual cells, dispersing within the cytoplasm or clustering around the nuclear membrane. Based on these observations, they concluded that the mode of NiO NP-induced toxicity lies in their ability to

access cells, leading to damage within essential organelles like the nucleus, peroxisomes, or mitochondria.

sp-ICP-MS was applied to identify NiO NPs (approx. 40 nm) in different soybean tissues, aiming to better comprehend the uptake and translocation of NiO NPs and Ni^{2+} within the plant (Zhou et al., 2023). According to the findings of the study, as the transport distance from the roots increased, the content of NiO NPs decreased. The higher concentration of NPs observed in the roots compared to shoots was attributed in part to the absorption of these particles on the surface of the plant roots. Additionally, an increase in the average particle size of NiO NPs was noted in the roots and seeds as the applied concentration of NiO NPs increased. The study also revealed that only minimal amounts of NPs could theoretically penetrate the plant through the cell wall pores. Considering the root system as the primary site of NiO NPs exposure, the researchers speculated that an elevated concentration possibly led to increased root secretions, potentially hindering further uptake by the plant.

Recent studies have confirmed that NiO nanoparticles can penetrate plant systems, primarily accumulating in the roots. Advanced imaging and chemical mapping techniques have been instrumental in detecting these nanoparticles within plant tissues (Fig. 1).

4. Phytotoxicity of Ni NPs: different scales of direct effects

Understanding the potential toxic effects of NiO NPs is essential when considering their application in agriculture, ensuring both environmental safety and optimal efficacy. Despite of these, the potential phytotoxicity of NiO NPs remains inadequately understood. In general, the impact of NPs on the metabolism and development of plants, depends on the chemistry, concentrations, and sizes of the NPs applied (Dietz and Herth, 2011; Chahardoli et al., 2020). It is thought that smaller particles exhibit increased toxicity due to their larger active surface area, facilitating more interactions with their environment (Yin et al., 2011; Yan and Chen, 2019; Scherer et al., 2019). Moreover, smaller particles have an increased ability to penetrate the interior of plant cells, potentially causing damage. The presence of Ni NPs may exert direct toxic effects on plants and these effects manifest at different scales from cellular to whole plant level (Fig. 2).

It is widely accepted that NiO NPs exert their multilevel negative effects on plants primarily by disrupting the homeostasis of reactive oxygen species (ROS). Changes in activities of ascorbate peroxidase (APX), catalase (CAT), superoxide dismutase (SOD), glutathione peroxidase, glutathione reductase (GR), glutathione-*S*-transferase, polyphenol oxidase, phenylalanine ammonia-lyase as well as elevated contents of glutathione (GSH), ascorbic acid (AsA), methylglyoxal, glucosinolates and phenolic compounds have been observed in NiO NP-treated plants species like *Nigella arvensis*, *Dracocephalum kotschyi*, *Brassica rapa, Solanum lycopersicum, Foeniculum vulgare, Raphanus sativus, Lycium barbarum*, T*riticum aestivum, Allium cepa* (Chahardoli et al., 2020; Chahardoli, 2023; Chung et al., 2019; Pinto et al., 2019; Saleh et al., 2019; Faisal et al., 2013; Besharat et al., 2021; Abdel-Salam et al., 2018; Manna and Bandyopadhyay, 2023). In addition to enzyme activities, the up-regulating effect of NiO NPs also manifested on gene expressions related to oxidative stress (Chung et al., 2019; Soares et al., 2018; Manna et al., 2021), on MYB transcription factors, and on phenolic compounds (Chung et al., 2019). The NiO NP-triggered changes in antioxidant activities and contents result in ROS (especially hydrogen peroxide, H$_2$O$_2$) accumulation in multiple plant species (Oukarroum et al., 2015; Abdel-Salam et al., 2018; Baskar et al., 2018; Saleh et al., 2019; Chahardoli et al., 2020; Chung et al., 2019; Pinto et al., 2019; Manna et al., 2021; Manna and Bandyopadhyay, 2023). In addition to ROS, NiO NPs induce the production of nitric oxide (NO) in *Allium cepa* roots possibly due to promoted nitrate reductase activity (Manna et al., 2021). Recently, moderately elevated NO, peroxynitrite levels and altered *S*-nitrosoglutathione reductase enzyme activity and protein abundance have been observed in Ni hyperaccumulator species
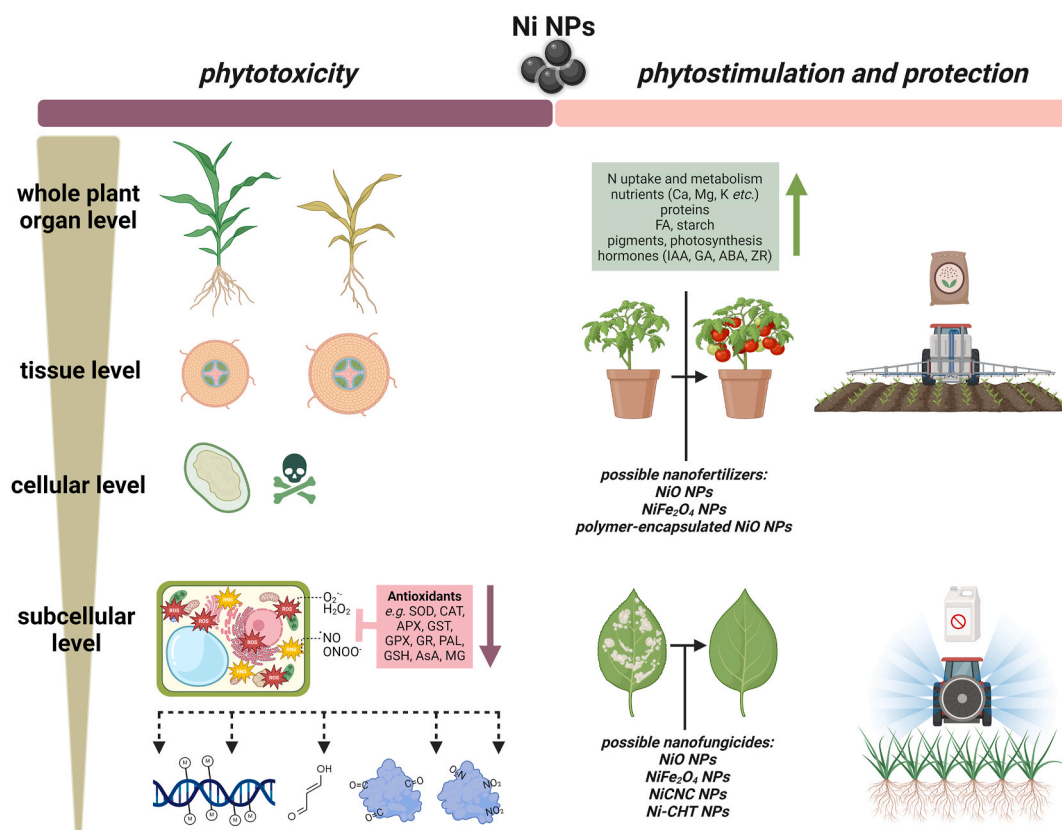
Fig. 2. The phytotoxic *vs.* phytostimulative effects of Ni NPs. See explanation in the text. Abbreviations: Ni NPs, nickel nanoparticles; ROS, reactive oxygen species; $O_2^{\bullet-}$, superoxide anion radical; H_2O_2, hydrogen peroxide; $^{\bullet}NO$, nitric oxide; $ONOO^-$, peroxynitrite, SOD, superoxide dismutase; CAT, catalase; APX, ascorbate peroxidase; GST, glutathione-*S*-transferase; GPX, glutathione peroxidase; GR, glutathione reductase; PAL, phenylalanine ammonia-lyase; GSH, glutathione; AsA ascorbate; MG methylglyoxal; FA, fatty acid; IAA, indole-3-acetic acid; GA, gibberellic acid; ABA, abscisic acid; ZR, zeatin riboside; NiO NPs, nickel oxide nanoparticles; NiFe$_2$O$_4$ NPs, nickel ferrite nanoparticles; NiCNC NPs, nickel-chitosan nanoconjugate nanoparticles; Ni-CHT NPs, nickel-chitosan nanoparticles.

indicating that in addition to the oxidative processes also the nitrosative signaling is affected by NiO NPs. As a consequence, in the proteome, changes in the rate of protein tyrosine nitration are caused by NiO NPs (Kondak et al., 2024). In the case of NiO NP-induced ROS, the effects on proteins are barely known (Saleh et al., 2019), but the elevation of malondialdehyde levels indicating lipid peroxidation has been revealed by several studies (Manna and Bandyopadhyay, 2017b; Abdel-Salam et al., 2018; Saleh et al., 2019; Baskar et al., 2018; Chung et al., 2019; Pinto et al., 2019; Besharat et al., 2021). The effects of NiO NPs on plants' oxidative processes are summarized in Table 1. The effect of oxidative stress on nucleic acids may manifest as genotoxicity, one of the well-characterized subcellular-level effect of NiO NPs in plants. NiO NP has been shown to disrupt the regular cell division frequency and triggers chromosomal abnormalities, chromosome breaks consequently disrupting the cell cycle in correlation with dosage. Moreover, clastogenic and mito-depressive traits have also been described in NiO NP-exposed *Allium cepa* model plants (Manna and Bandyopadhyay, 2017a, Manna et al., 2022).

Regarding cellular level damage, all of the above NiO NP-induced processes lead to mitochondrial-dependent apoptotic cell death, which is characterized by mitochondrial dysfunction, an increase in the number of apoptotic and necrotic cells, and an increase in caspase-3-like protease activity (Faisal et al., 2013). Furthermore, NiO-NP exposure triggers DNA hypermethylation due to oxidative burst (H_2O_2 and NO generations), and leads to induction of autophagy, apoptotic and necrotic cell death pathways depending on NiO NP dosages (Manna et al., 2023). The compositional changes (pectin accumulation, formation of an exodermal suberin layer) observed in the root cell walls of the Ni hyperaccumulator species may contribute to the exclusion of NiO NPs

from the cytoplasm and delay metal ion or metal nanoparticle uptake (Kondak et al., 2024).

Cell wall-associated changes caused by NiO NPs increase cortex tissue thickness which may support tolerance during Ni overload since it may provide resistance to radial water flow and thus reduce heavy metal transport (Kondak et al., 2024). An additional mechanism that may contribute to the negative effects of NiO NP is disturbed ionic homeostasis, as the Na/K ratio and Fe, Mg content decrease in non-Ni-accumulating *Allium cepa* (Manna et al., 2021, 2023), while in Ni hyperaccumulator ecotypes, the homeostasis of cations (K, Na, Ca, Mg) is stable despite the high NiO NP load (Kondak et al., 2024). Damage caused by NiO NPs in subcellular, cellular and tissue processes results in organ-level effects such as limitation of root and shoot development. NiO NPs cause reductions in root elongation and fresh/dry biomass even in Ni hyperaccumulator species depending on ecotype and NP dosage (Kondak et al., 2024). Furthermore, a decrease in root and shoot biomass due to elevating NiO NP concentrations was shown in *Solanum lycopersicum*, *Raphanus sativus*, *Solanum melongena*, *Triticum aestivum*, *Nigella arvensis* and *Lycium barbarum* (Faisal et al., 2013; Abdel-Salam et al., 2018; Baskar et al., 2018; Pinto et al., 2019; Saleh et al., 2019; Chahardoli et al., 2020). NiO NPs exert a negative effect on the amount of photosynthetic pigments (chlorophylls, carotenoids), and in *Lemna gibba* on the photosynthetic electron transport performance (Chung et al., 2019; Pinto et al., 2019; Oukarroum et al., 2015; Saleh et al., 2019). The phytotoxic effects of Ni NPs manifested at different levels are depicted in Fig. 2.

Table 1

The effects of NiO NPs on the oxidative processes of plants. Abbreviations: ROS, reactive oxygen species; H_2O_2, hydrogen peroxide; SOD, superoxide dismutase; CAT, catalase; APX, ascorbate peroxidase; GST, glutathione-*S*-transferase; GSH, glutathione; AsA, ascorbate; NiO NPs, nickel oxide nanoparticles; PSII, photosystem II; MDA, malondialdehyde; GSSG, oxidized glutathione; POD, peroxidase; GSL, glucosinolate; DPPH, 2,2-diphenyl-1-picryl hydrazyl; RCA, rubisco activase.

Plant name	Part of the plant examined	Size of NP (nm)	Effect of NP on oxidative and nitrosative processes	References
Solanum lycopersicum	Roots	23.34	Higher activities of antioxidants (SOD, CAT and GSH). Increased ROS levels.	Faisal et al. (2013)
Solanum melongena	Seedlings (shoot and root)	10–20	Increased intracellular ROS formation and MDA production. The non-enzymatic antioxidants such as flavonoids and phenolics were altered in NP-treated plants.	Baskar et al. (2018)
Lemna gibba	Roots and leaves	30	Increased ROS levels. Induced a strong inhibitory effect on the PSII quantum yield, indicated an alteration of the photosynthetic electron transport performance.	Oukarroum et al. (2015)
Raphanus sativus	Seeds	23.3	Inducing toxicity, lipid peroxidation and membrane damage, ROS generation, and antioxidant activities. Concentration-dependent changes in activity of antioxidants (GSH, CAT, SOD).	Abdel-Salam et al. (2018)
Hordeum vulgare	Roots and leaves	7–14	Induced the occurrence of oxidative stress.	Soares et al. (2018)
Foeniculum vulgare	Shoots and roots	0.01–10	Increased MDA. Decrease in the amount of dehydrogenase enzyme in the root.	Besharat et al. (2021)
Lycium barbarum	Shoots	100	Induced oxidative damage by increasing lipid peroxidation and ROS content. Enzymatic (SOD, CAT and APX) and non-enzymatic (AsA, GSH, proline and phenols) antioxidant	Pinto et al. (2019)

Table 1 (*continued*)

Plant name	Part of the plant examined	Size of NP (nm)	Effect of NP on oxidative and nitrosative processes	References
Triticum aestivum	Roots and leaves	54	mechanisms activated. Increased the levels of antioxidants. Improved the antioxidant defense system and maintained AsA/DHA and GSH/GSSG redox balances.	Saleh et al. (2019)
Brassica rapa ssp. *pekinensis*	Seedlings (shoot and root)	10–20	Increased levels of H_2O_2 and total ROS, and antioxidant enzyme (POD) activity, transcript levels of genes coding for antioxidant enzymes (CAT, POD, and GST) and phytochemicals (GSLs, phenolics, and flavonoids).	Chung et al. (2019)
Nigella arvensis	Shoots and roots	5–8	Enhanced activities of antioxidant enzymes (CAT, POD, APX and SOD) and antioxidant compounds (total iridoids, total saponin, and total phenolic) along with DPPH scavenging activity, total antioxidant capacity and total reducing power.	Chahardoli et al. (2020)
Allium cepa	Roots	<50	Increased cellular H_2O_2 content. Significant decrease of NO at higher concentrations of NiO NP while cellular ROS continued to increase. CAT, SOD, and APX, and the RCA showed upregulation.	Manna et al. (2021)
Allium cepa	Roots	<50	Intracellular methylglyoxal, H_2O_2 levels increased significantly. Major damages to the AsA-GSH cycle.	Manna and Bandyopadhyay (2023)
Dracocephalum kotschyi	Shoots and roots	10–20	Induced hormetic effects on photosynthetic pigments. Toxic effects and oxidative stress	Chahardoli (2023)

Table 1 (*continued*)

Plant name	Part of the plant examined	Size of NP (nm)	Effect of NP on oxidative and nitrosative processes	References
			caused by NPs. Increasing the activities of SOD, POD, CAT, and APX.	

5. Mitigation strategies against NiO NP-induced phytotoxicity

The toxic symptoms of NiO NP stress can be ameliorated by exogenous treatments performing induced defence in non-tolerant plant species, while Ni hyperaccumulator/tolerant species possesses endogenous protection mechanisms against Ni NPs.

As an example for exogenously induced defence, Soares et al. (2018) evaluated the possible impact of silicon dioxide (SiO_2) NP on improving the tolerance of *Hordeum vulgare* against NiO NP. Exposure to NiO NP alone adversely affected barley growth and photosynthetic functions; and co-exposure with nano-SiO_2 partially alleviated the negative effects of NiO NP. The molecular mechanism of the beneficial effect of SiO_2 NP proved to be the limitation of the NiO NP-triggered superoxide production and lipid peroxidation by the activation of antioxidant enzymes such as APX and CAT. Additionally, SiO_2 NP treatment resulted in elevated Ni content in the root system suggesting that nano-SiO_2 triggers Ni compartmentation and accumulation in roots as a defense mechanism to limit its translocation to aboveground organs.

Exogenously administered AsA in NiO NP-exposed plants alleviates the inhibition in root elongation and the macroscopic phytotoxic effects in *Solanum lycopersicum* seedlings (Spormann et al., 2022). Moreover, AsA supplementation significantly reduced H_2O_2 levels in the roots of NiO NP-treated plants mainly by the increment of AsA, GSH and total phenols. Among antioxidant enzymes, the activity of SOD and GR is induced by AsA addition, implying that exogenous AsA activates antioxidant detoxification in case of NiO NP stress (Spormann et al., 2022).

Interestingly, the changes of an environmental condition may trigger mitigation processes against the NiO NP phytotoxicity. NiO NP-treated *Triticum aestivum* grown in the presence of elevated carbon dioxide (eCO_2, 620 ppm) showed promoted photosynthesis and inhibited photorespiration, resulting in reduced ROS production compared to plants grown in the presence of ambient CO_2 (aCO_2, 400 ppm, Saleh et al., 2019). Moreover, in case of eCO_2 condition, due to limited ROS formation, protein and lipid oxidation is reduced compared to NiO NPs + aCO_2. Additionally, eCO_2 results in elevated peroxidase activity, increased phenol, tocopherol contents and maintained AsA/DHA and GSH/GSSG redox balances. These results imply the possibility that wheat plants will be more tolerant to NiONPs stress under future climate CO_2 (Saleh et al., 2019).

Hyperaccumulator plants have the capacity to accumulate over 1000 mg/kg of Ni in their shoots without toxic symptoms meaning that Ni hyperaccumulation is coupled with Ni hypertolerance (Hipfinger et al., 2022). The study by Kondak et al. (2024) examined the endogenous defence mechanisms and revealed that the endurance of *Odontarrhena lesbiaca* ecotypes against NiO NPs manifests at cellular (binding of NPs by the root cell wall due to compositional modification), tissue (root anatomical changes), organ/organism (slight modifications in biomass production) and molecular (changes in reactive nitrogen species metabolism and induced nitrosative protein modification) levels.

6. The beneficial side of Ni NPs: nanofungicides and nanofertilizers

Plants are continuously affected by other organisms living in their environment, and the biotic factors such as fungi, bacteria, viruses,

insects induce loss in crop yield probably more than the cumulative losses caused by all other stress factors (Saddique et al., 2018). Different networks of signals and responses participate in creating plant tolerance against biotic stress, and these networks provide an intricate mechanism to help plants coping with pathogen attacks (Khoshru et al., 2023). It has been revealed that the endogenous defence pathways mainly against fungal pathogens can be activated by exogenous administration of NiO NPs.

Fusarium wilt, a common vascular wilt fungal disease, is a significant challenge in vegetable farming. Ni NPs exert antifungal properties against two specific forms of *Fusarium oxysporum* (*F. oxysporum* f. sp. *lactucae* and *F. oxysporum* f. sp. *lycopersici*) affecting lettuce and tomato plants in controlled laboratory and greenhouse settings. Ni NPs were shown to impede the growth and spore production of the fungi *in vitro*. When applied in the greenhouse, the use of Ni NPs exhibited substantial decline in disease severity in lettuce and tomato shedding light on the potential of Ni NPs as a valuable tool in managing this agricultural concern (Ahmed et al., 2016). Similarly, the *in vitro* antimycotic properties of nickel (and cobalt) ferrite ($NiFe_2O_4$ and $CoFe_2O_4$) NPs against three phytopathogenic fungi (*Fusarium oxysporum*, *Colletotrichum gloeosporioides*, and *Dematophora necatrix*) has been evidenced (Sharma et al., 2017). Furthermore, $NiFe_2O_4$ NPs supplementation concentration dependently limited disease incidence (%) in *Fusarium*-infected *Capsicum annuum* implying the possibility of using $NiFe_2O_4$ NPs as potent fungicides in managing plant diseases (Sharma et al., 2017).

Nickel-chitosan nanoconjugates (NiCNC, 300–400 nm) have been shown to exert *in vitro* antifungal effect against *Fusarium solani* which manifested in reduced mycelium radial growth, inhibited spore germination and sporulation, spore viability possibly due to ROS-mediated lipid peroxidation. In case of *F. solani*-inoculated wheat seedlings, NiCNC supplementation resulted in a reduction of disease incidence (%), increased shoot and root growth and vigor index (%) in comparison with untreated seedlings (Chouhan et al., 2022).

Recently, smaller nickel-chitosan nanoparticles (Ni-CHT NPs, spherical within 20–70 nm) have been prepared and examined as alternatives to fungicides for combating rice blast caused by *Pyricularia oryzae*. The application of Ni-CHT caused notable improvement in germination, shoot and root growth capability of *Oryza sativa* partly due to the Ni NP-induced appearance of new polypeptides (Rubisco units) enabling the enhanced photosynthesis. More importantly, Ni-CHT NP-treated rice plants showed diminished blast symptoms on their leaves and the Ni NP treatment displays inhibition of mycelia development in Petri dishes (Parthasarathy et al., 2023).

Due to the fact that Ni is an essential microelement for plants, its application within an optimal concentration range stimulates the plant growth. Conventional nutrient fertilizers possess high release rates overwhelming the actual nutrient absorption rate by plants which results in low nutrient use efficiencies. Application of Ni and other nutrients in nano-format for fertilizing plants may be beneficial due to slow nutrient release and increased nutrient use efficiency (Zulfiqar et al., 2019).

Some recent studies focus on the application of different Ni nanoforms in order to improve plant vegetative growth and yield. The comprehensive study of Zhou et al. (2023) in which NiO NPs, bulk NiO (b-NiO), and nickel sulphate ($NiSO_4$) were supplied through the soil for *Glycine* max demonstrated that NiO NPs can be directly accumulated by plants and transferred to soybean seeds in particulate form. Furthermore, realistic dosage of NiO NPs has been shown to effectively improve soybean yield and nutritional quality (increased fatty acid and starch contents) by promoting plant photosynthesis and regulating nitrogen metabolism and hormone levels (indole-3-acetic acid, gibberellic acid, abscisic acid, zeatin riboside).

Recently, Ni encapsulated NPs with different biodegradable coatings such as starch, polyvinyl alcohol, gum arabica, gelatin, molasses and paraffin wax have been prepared and applied for *in soil* treatment of *Chloris gayana* (Beig et al., 2023). Findings demonstrated that the

application of Ni-coated NPs onto urea granules notably elevated nitrogen accessibility, consequently boosting the dry matter production of Rhode grass. Additionally, $NiFe_2O_4$ NPs (12.5 ± 0.5 nm) have been observed to taken up by the barley roots, translocated to shoot and significantly increase calcium, magnesium, potassium, sodium and manganese, chlorophyll, carotenoid, and soluble protein contents without promoting plant biomass production (Tombuloglu et al., 2019) (Fig. 2).

7. Conclusion and future research directions

The increased production and spread of Ni NMs into the environment may directly and indirectly affect plants. Balancing the beneficial effects and adverse impacts of Ni NPs requires precise dosing strategies to harness Ni NPs' positive attributes in crop production effectively.

- Advancements in analytical spectroscopy and imaging are expected to improve the detectable size range of NiO nanoparticles and the detection limit of Ni-ions. This will allow better spatial resolution and the possibility to investigate finer effects related to Ni-containing chemical species in plants. In-field applicable elemental mapping technologies, such as LIBS instrumentation, show promise for agricultural relevance.
- The molecular details of Ni NP phytotoxicity are emerging, with direct toxicity based on disrupting ROS homeostasis by modifying antioxidants at both activity and gene levels. Future studies should investigate the effects of ROS and reactive nitrogen species on macromolecules and distinguish NP-associated effects from Ni ion effects. NiO NP-triggered oxidative stress's consequences should be explored at cellular, tissue, and organ levels for a comprehensive understanding.
- Indirect effects of NiO NPs on ecological partners like rhizobacteria, mycorrhiza, and pollinators remain a significant knowledge gap. The interaction of Ni NPs with other NMs in the plant-soil system and co-stress effects on plants are also underexplored areas.
- Ameliorating NiO NP toxicity in non-tolerant plants can be achieved through exogenous treatments or environmental condition alterations, targeting oxidative stress. Hyperaccumulating plant species possess endogenous defense mechanisms against NiO NP stress. Exploring additional beneficial agents for Ni NP stress mitigation holds practical relevance.
- Ni NPs also show promise in alleviating plant stress and exhibiting beneficial effects in agriculture, such as managing Fusarium wilt and other fungal diseases. The application of Ni NPs as nanofertilizers is emerging, and further exploration is essential to fully leverage their benefits for enhanced stress tolerance and plant health.

CRediT authorship contribution statement

Selahattin Kondak: Writing – review & editing, Writing – original draft. **Dóra Kondak:** Writing – review & editing. **Onur Kabadayi:** Writing – review & editing, Writing – original draft. **László Erdei:** Writing – review & editing. **Andrea Rónavári:** Writing – review & editing, Writing – original draft. **Zoltán Kónya:** Writing – review & editing. **Gábor Galbács:** Writing – review & editing, Writing – original draft, Funding acquisition. **Zsuzsanna Kolbert:** Writing – review & editing, Writing – original draft, Visualization, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdel-Salam, E.M., Qahtan, A.A., Faisal, M., Saquib, Q., Alatar, A.A., Al-Khedhairy, A.A., 2018. Phytotoxic assessment of nickel oxide (NiO) nanoparticles in radish. Phytotoxicity of Nanoparticles. Springer, Cham, pp. 269–284. https://doi.org/10.1007/978-3-319-76708-6_11.

Ahmad, W., Bhatt, S.C., Verma, M., Kumar, V., Kim, H., 2022. A review on current trends in the green synthesis of nickel oxide nanoparticles, characterizations, and their applications. Environ. Nanotechnol. Monit. Manag. 18, 100674 https://doi.org/10.1016/j.enmm.2022.100674.

Ahmed, A.I., Yadav, D.R., Lee, Y.S., 2016. Applications of nickel nanoparticles for control of Fusarium wilt on lettuce and tomato. Int. J. Innov. Res. Sci. Eng. Technol. 5 (5), 7378–7385. https://doi.org/10.15680/IJIRSET.2016.0505132.

Arruda, S.C.C., Silva, A.L.D., 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.

Baskar, V., Nayeem, S., Kuppuraj, S.P., Muthu, T., Ramalingam, S., 2018. Assessment of the effects of metal oxide nanoparticles on the growth, physiology and metabolic responses in in vitro grown eggplant (*Solanum melongena*). 3 Biotech 8, 1–12. https://doi.org/10.1007/s13205-018-1386-9.

Beig, B., Niazi, M.B.K., Jahan, Z., Zia, M., Shah, G.A., Iqbal, Z., 2023. Biodegradable polymer encapsulated nickel nanoparticles for slow release urea promotes Rhode grass yield and nitrogen recovery. J. Polym. Environ. 31 (5), 1866–1883. https://doi.org/10.1007/s10924-022-02729-2.

Besharat, H., Khavari-Nejad, R.A., Mahmoodzadeh, H., Abadi, K.N.S., 2021. Effect of nano and bulk nickel oxide on biomass and antioxidant enzymes production of fennel. Agritech 41 (1), 71–84. https://doi.org/10.22146/agritech.55643.

Bhoye, M., Pansambal, S., Basnet, P., Lin, K.Y.A., Gutierrez-Mercado, K.Y., Pérez-Larios, A., et al., 2023. Eco-friendly synthesis of Ni/NiO nanoparticles using Gymnema sylvestre leaves extract for antifungal activity. J. Compos. Sci. 7 (3), 105. https://doi.org/10.3390/jcs7030105.

Busser, B., Moncayo, S., Coll, J.L., Sancey, L., Motto-Ros, V., 2018. Elemental imaging using laser-induced breakdown spectroscopy: a new and promising approach for biological and medical applications. Coord. Chem. Rev. 358, 70–79. https://doi.org/10.1016/j.ccr.2017.12.006.

Castillo-Michel, H.A., Larue, C., Del Real, A.E.P., Cotte, M., Sarret, G., 2017. Practical review on the use of synchrotron based micro-and nano-X-ray fluorescence mapping and X-ray absorption spectroscopy to investigate the interactions between plants and engineered nanomaterials. Plant Physiol. Biochem. 110, 13–32. https://doi.org/10.1016/j.plaphy.2016.07.018.

Chahardoli, A., Karimi, N., Ma, X., Qalekhani, F., 2020. Effects of engineered aluminum and nickel oxide nanoparticles on the growth and antioxidant defense systems of *Nigella arvensis*. L. Sci. Rep. 10 (1), 3847. https://doi.org/10.1038/s41598-020-60841-6.

Chahardoli, A., 2023. Hormetic dose responses induced by nickel oxide nanoparticles (NiONPs) on growth, biochemical, and antioxidant defense systems of *Dracocephalum kotschyi*. Environ. Sci. Pollut. Res. 1–17. https://doi.org/10.1007/s11356-023-29359-y.

Chen, D.H., Wu, S.H., 2000. Synthesis of nickel nanoparticles in water-in-oil microemulsions. Chem. Mater. 12 (5), 1354–1360. https://doi.org/10.1021/cm991167y.

Chouhan, D., Dutta, A., Kumar, A., Mandal, P., Choudhuri, C., 2022. Application of nickel chitosan nanoconjugate as an antifungal agent for combating *Fusarium* rot of wheat. Sci. Rep. 12 (1), 14518 https://doi.org/10.1038/s41598-022-18670-2.

Chung, I.M., Venkidasamy, B., Thiruvengadam, M., 2019. Nickel oxide nanoparticles cause substantial physiological, phytochemical, and molecular-level changes in Chinese cabbage seedlings. Plant Physiol. Biochem. 139, 92–101. https://doi.org/10.1016/j.plaphy.2019.03.010.

de Oliveira, J.B., Marques, J.P.R., Rodak, B.W., Galindo, F.S., Carr, N.F., Almeida, E., et al., 2022. Fate of nickel in soybean seeds dressed with different forms of nickel. Rhizosphere 21, 100464. https://doi.org/10.1016/j.rhisph.2021.100464.

De Souza-Torres, A., Govea-Alcaide, E., Gomez-Padilla, E., Masunaga, S.H., Effenberger, F.B., Rossi, L.M., et al., 2021. Fe3O4 nanoparticles and *Rhizobium inoculation* enhance nodulation, nitrogen fixation and growth of common bean plants grown in soil. Rhizosphere 17, 100275. https://doi.org/10.1016/j.rhisph.2020.100275.

Dietz, K.J., Herth, S., 2011. Plant nanotoxicology. Trends Plant Sci. 16 (11), 582–589. https://doi.org/10.1016/j.tplants.2011.08.003.

Dong, R., Li, Y., Li, W., Zhang, H., Liu, Y., Ma, L., et al., 2019. Recent developments in luminescent nanoparticles for plant imaging and photosynthesis. J. Rare Earths 37 (9), 903–915. https://doi.org/10.1016/j.jre.2019.04.001.

Fabiano, C.C., Tezotto, T., Favarin, J.L., Polacco, J.C., Mazzafera, P., 2015. Essentiality of nickel in plants: a role in plant stresses. Front. Plant Sci. 6, 754. https://doi.org/10.3389/fpls.2015.00754.

Faisal, M., Saquib, Q., Alatar, A.A., Al-Khedhairy, A.A., Hegazy, A.K., Musarrat, J., 2013. Phytotoxic hazards of NiO-nanoparticles in tomato: a study on mechanism of cell death. J. Hazard Mater. 250, 318–332. https://doi.org/10.1016/j.jhazmat.2013.01.063.

Galazzi, R.M., Chacón-Madrid, K., Freitas, D.C., da Costa, L.F., Arruda, M.A.Z., 2020. Inductively coupled plasma mass spectrometry based platforms for studies involving nanoparticle effects in biological samples. Rapid Commun. Mass Spectrom. 34 (S3), e8726 https://doi.org/10.1002/rcm.8726.

Galbács, G., Kéri, A., Kohut, A., Veres, M., Geretovszky, Z., 2021. Nanoparticles in analytical laser and plasma spectroscopy–a review of recent developments in methodology and applications. J. Anal. At. Spectrom. 36 (9), 1826–1872. https://doi.org/10.1039/D1JA00149C.

Gebretinsae, H.G., Tsegay, M.G., Nuru, Z.Y., 2021. Biosynthesis of nickel oxide (NiO) nanoparticles from cactus plant extract. Mater. Today: Proc. 36, 566–570. https://doi.org/10.1016/j.matpr.2020.05.331.

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M.S., Catalano, A., 2020. Nickel: human health and environmental toxicology. Int. J. Environ. Res. Publ. Health 17 (3), 679. https://doi.org/10.3390/ijerph17030679.

Gnach, A., Lipinski, T., Bednarkiewicz, A., Rybka, J., Capobianco, J.A., 2015. Upconverting nanoparticles: assessing the toxicity. Chem. Soc. Rev. 44 (6), 1561–1584. https://doi.org/10.1039/c4cs00177j.

González-Melendi, P., Fernández-Pacheco, R., Coronado, M.J., Corredor, E., Testillano, P.S., Risueño, M.C., Pérez-de-Luque, A., 2008. Nanoparticles as smart treatment-delivery systems in plants: assessment of different techniques of microscopy for their visualization in plant tissues. Ann. Bot. 101 (1), 187–195. https://doi.org/10.1093/aob/mcm283.

Hamdan, A.M., Sardi, A., Reksamunanda, r R.P., Maulida, Z., Arsa, D.A., Lubis, S.S., Nisah, K., 2024. Green synthesis of NiO nanoparticles using a Cd hyperaccumulator (*Lactuca sativa* L.) and its application as a Pb(II) and Cu(II) adsorbent. Environ. Nanotechnol. Monit. Manag. 21, 100910 https://doi.org/10.1016/j.enmm.2023.100910.

Hedfi, A., Mahmoudi, E., Boufahja, F., Beyrem, H., Aissa, P., 2007. Effects of increasing levels of nickel contamination on structure of offshore nematode communities in experimental microcosms. Bull. Environ. Contam. Toxicol. 79, 345–349. https://doi.org/10.1007/s00128-007-9261-0.

Hipfinger, C., Laux, M., Puschenreiter, M., 2022. Comparison of four nickel hyperaccumulator species in the temperate climate zone of Central Europe. J. Geochem. Explor. 234, 106933 https://doi.org/10.1016/j.gexplo.2021.106933.

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

Hossain, M.D., Mayanovic, R.A., Dey, S., Sakidja, R., Benamara, M., 2018. Room-temperature ferromagnetism in Ni (ii)-chromia based core–shell nanoparticles: experiment and first principles calculations. Phys. Chem. Chem. Phys. 20 (15), 10396–10406. https://doi.org/10.1039/C7CP08597D.

Jaji, N.D., Lee, H.L., Hussin, M.H., Akil, H.M., Zakaria, M.R., Othman, M.B.H., 2020. Advanced nickel nanoparticles technology: from synthesis to applications. Nanotechnol. Rev. 9 (1), 1456–1480. https://doi.org/10.1515/ntrev-2020-0109.

Khan, S.A., Shahid, S., Ayaz, A., Alkahtani, J., Elshikh, M.S., Riaz, T., 2021. Phytomolecules-coated NiO nanoparticles synthesis using *Abutilon indicum* leaf extract: antioxidant, antibacterial, and anticancer activities. Int. J. Nanomed. 1757–1773. https://doi.org/10.2147/IJN.S294012.

Khoshru, B., Mitra, D., Joshi, K., Adhikari, P., Rion, M.S.I., Fadiji, A.E., et al., 2023. Decrypting the multi-functional biological activators and inducers of defense responses against biotic stresses in plants. Heliyon 9 (3), e13825. https://doi.org/10.1016/j.heliyon.2023.e13825.

Kondak, S., Janovszky, P., Szőllősi, R., Molnár, Á., Oláh, D., Adedokun, O.P., et al., 2024. Nickel oxide nanoparticles induce cell wall modifications, root anatomical changes, and nitrosative signaling in ecotypes of Ni hyperaccumulator *Odontarrhena lesbiaca*. Environ. Pollut. 341, 122874 https://doi.org/10.1016/j.envpol.2023.122874.

Kopittke, P.M., Punshon, T., Paterson, D.J., Tappero, R.V., Wang, P., Blamey, F.P.C., et al., 2018. Synchrotron-based X-ray fluorescence microscopy as a technique for imaging of elements in plants. Plant Physiol. 178 (2), 507–523. https://doi.org/10.1104/pp.18.00759.

Kumar, C.R., Betageri, V.S., Nagaraju, G., Pujar, G.H., Suma, B.P., Latha, M.S., 2020. Photocatalytic, nitrite sensing and antibacterial studies of facile bio-synthesized nickel oxide nanoparticles. J. Sci.: Adv. Mater. Devices 5 (1), 48–55. https://doi.org/10.1016/j.jsamd.2020.02.002.

Kurczyńska, E., Godel-Jędrychowska, K., Sala, K., Milewska-Hendel, A., 2021. Nanoparticles—plant interaction: what we know, where we are? Appl. Sci. 11, 5473. https://doi.org/10.3390/app11125473.

Laycock, A., Clark, N.J., Clough, R., Smith, R., Handy, R.D., 2022. Determination of metallic nanoparticles in biological samples by single particle ICP-MS: a systematic review from sample collection to analysis. Environ. Sci.: Nano 9 (2), 420–453. https://doi.org/10.1039/D1EN00680K.

Li, W., Kaminski Schierle, G.S., Lei, B., Liu, Y., Kaminski, C.F., 2022. Fluorescent nanoparticles for super-resolution imaging. Chem. Rev. 122 (15), 12495–12543. https://doi.org/10.1021/acs.chemrev.2c00050.

Lin, D., Xing, B., 2007. Phytotoxicity of nanoparticles: inhibition of seed germination and root growth. Environ. Pollut. 150 (2), 243–250. https://doi.org/10.1016/j.envpol.2007.01.016.

Loeschner, K., Johnson, M.E., Montoro Bustos, A.R., 2023. Application of single particle ICP-MS for the determination of inorganic nanoparticles in food additives and food: a short review. Nanomaterials 13 (18), 2547. https://doi.org/10.3390/nano13182547.

Malatesta, M., 2021. Transmission electron microscopy as a powerful tool to investigate the interaction of nanoparticles with subcellular structures. Int. J. Mol. Sci. 22 (23), 12789 https://doi.org/10.3390/ijms222312789.

Manna, I., Bandyopadhyay, M., 2017a. Engineered nickel oxide nanoparticles affect genome stability in *Allium cepa* (L.). Plant Physiol. Biochem. 121, 206–215. https://doi.org/10.1016/j.plaphy.2017.11.003.

Manna, I., Bandyopadhyay, M., 2017b. Engineered nickel oxide nanoparticle causes substantial physicochemical perturbation in plants. Front. Chem. 5, 92. https://doi.org/10.3389/fchem.2017.00092.

Manna, I., Sahoo, S., Bandyopadhyay, M., 2021. Effect of engineered nickel oxide nanoparticle on reactive oxygen species–nitric oxide interplay in the roots of *Allium cepa* L. Front. Plant Sci. 12, 586509 https://doi.org/10.3389/fpls.2021.586509.

Manna, I., Mishra, S., Bandyopadhyay, M., 2022. In vivo genotoxicity assessment of nickel oxide nanoparticles in the model plant *Allium cepa* L. Nucleus 65, 203–214. https://doi.org/10.1007/s13237-021-00377-w.

Manna, I., Bandyopadhyay, M., 2023. The impact of engineered nickel oxide nanoparticles on ascorbate glutathione cycle in *Allium cepa* L. Physiol. Mol. Biol. Plants 29 (5), 663–678. https://doi.org/10.1007/s12298-023-01314-8.

Manna, I., Sahoo, S., Bandyopadhyay, M., 2023. Dynamic changes in global methylation and plant cell death mechanism in response to NiO nanoparticles. Planta 257 (5), 93. https://doi.org/10.1007/s00425-023-04127-x.

Mekuye, B., Abera, B., 2023. Nanomaterials: an overview of synthesis, classification, characterization, and applications. Nano Select. https://doi.org/10.1002/nano.202300038.

Mizuta, Y., 2021. Advances in two-photon imaging in plants. Plant Cell Physiol. 62 (8), 1224–1230. https://doi.org/10.1093/pcp/pcab062.

Modlitbová, P., Pořízka, P., Kaiser, J., 2020. Laser-induced breakdown spectroscopy as a promising tool in the elemental bioimaging of plant tissues. TrAC - Trends Anal. Chem. 122, 115729 https://doi.org/10.1016/j.trac.2019.115729.

Mustafa, A., Zulfiqar, U., Mumtaz, M.Z., Radziemska, M., Haider, F.U., Holatko, J., et al., 2023. Nickel (Ni) phytotoxicity and detoxification mechanisms: a review. Chemosphere 138574. https://doi.org/10.1016/j.chemosphere.2023.138574.

Nasrollahzadeh, M., Sajadi, S.M., 2015. Preparation of Au nanoparticles by *Anthemis xylopoda* flowers aqueous extract and their application for alkyne/aldehyde/amine A³-type coupling reactions. RSC Adv. 5 (57), 46240–46246. https://doi.org/10.1039/C5RA08927A.

Oliveira, H.C., Seabra, A.B., Kondak, S., Adedokun, O.P., Kolbert, Z., 2023. Multilevel approach to plant–nanomaterial relationships: from cells to living ecosystems. J. Exp. Bot. 74 (12), 3406–3424. https://doi.org/10.1093/jxb/erad107.

Oukarroum, A., Barhoumi, L., Samadani, M., Dewez, D., 2015. Toxic effects of nickel oxide bulk and nanoparticles on the aquatic plant *Lemna gibba* L. BioMed Res. Int. 2015 https://doi.org/10.1155/2015/501326.

Pakzad, K., Alinezhad, H., Nasrollahzadeh, M., 2019. Green synthesis of Ni@Fe₃O₄ and CuO nanoparticles using Euphorbia maculata extract as photocatalysts for the degradation of organic pollutants under UV-irradiation. Ceram. Int. 45 (14), 17173–17182. https://doi.org/10.1016/j.ceramint.2019.05.272.

Parsons, J.G., Lopez, M.L., Gonzalez, C.M., Peralta-Videa, J.R., Gardea-Torresdey, J.L., 2010. Toxicity and biotransformation of uncoated and coated nickel hydroxide nanoparticles on mesquite plants. Environ. Toxicol. Chem. 29 (5), 1146–1154. https://doi.org/10.1002/etc.146.

Parthasarathy, R., Jayabaskaran, C., Manikandan, A., Anusuya, S., 2023. Synthesis of nickel-chitosan nanoparticles for controlling blast diseases in asian rice. Appl. Biochem. Biotechnol. 195 (3), 2134–2148. https://doi.org/10.1007/s12010-022-04198-8.

Pinto, M., Soares, C., Pinto, A.S., Fidalgo, F., 2019. Phytotoxic effects of bulk and nano-sized Ni on *Lycium barbarum* L. grown *in vitro*–Oxidative damage and antioxidant response. Chemosphere 218, 507–516. https://doi.org/10.1016/j.chemosphere.2018.11.127.

Rónavári, A., Kovács, D., Igaz, N., Vágvölgyi, C., Boros, I.M., Kónya, Z., Pfeiffer, I., Kiricsi, M., 2017. Biological activity of green-synthesized silver nanoparticles depends on the applied natural extracts: a comprehensive study. Int. J. Nanomed. 12, 871–883. https://doi.org/10.2147/IJN.S122842.

Saddique, M., Kamran, M., Shahbaz, M., 2018. Differential responses of plants to biotic stress and the role of metabolites. In: Plant Metabolites and Regulation under Environmental Stress. Academic Press, pp. 69–87. https://doi.org/10.1016/B978-0-12-812689-9.00004-2.

Salata, O.V., 2004. Applications of nanoparticles in biology and medicine. J. Nanobiotechnol. 2 (1), 1–6. https://doi.org/10.1186/1477-3155-2-3.

Saleh, A.M., Hassan, Y.M., Selim, S., AbdElgawad, H., 2019. NiO-nanoparticles induce reduced phytotoxic hazards in wheat (*Triticum aestivum* L.) grown under future climate CO₂. Chemosphere 220, 1047–1057. https://doi.org/10.1016/j.chemosphere.2019.01.023.

Scherer, M.D., Sposito, J.C., Falco, W.F., Grisolia, A.B., Andrade, L.H., Lima, S.M., et al., 2019. Cytotoxic and genotoxic effects of silver nanoparticles on meristematic cells of *Allium cepa* roots: a close analysis of particle size dependence. Sci. Total Environ. 660, 459–467. https://doi.org/10.1016/j.scitotenv.2018.12.444.

Seiffert, S.B., Elinkmann, M., Niehaves, E., Vennemann, A., Mozhayeva, D., Kröger, S., et al., 2023. Calibration strategy to size and localize multi-shaped nanoparticles in tissue sections using LA–spICP–MS. Anal. Chem. 95 (15), 6383–6390. https://doi.org/10.1021/acs.analchem.3c00022.

Sembada, A.A., Lenggoro, I.W., 2024. Transport of nanoparticles into plants and their detection methods. Nanomaterials 14 (2), 131. https://doi.org/10.3390/nano14020131.

Sharma, P., Sharma, A., Sharma, M., Bhalla, N., Estrela, P., Jain, A., et al., 2017. Nanomaterial fungicides: in vitro and in vivo antimycotic activity of cobalt and nickel nanoferrites on phytopathogenic fungi. Global Challenges 1 (9), 1700041. https://doi.org/10.1002/gch2.201700041.

Singh, V.P., Singh, S., Tripathi, D.K., Prasad, S.M., Chauhan, D.K., 2021. Plant Responses to Nanomaterials. Springer International Publishing. https://doi.org/10.1007/978-3-030-36740-4.

Soares, C., Branco-Neves, S., de Sousa, A., Pereira, R., Fidalgo, F., 2016. Ecotoxicological relevance of nano-NiO and acetaminophen to *Hordeum vulgare* L.: combining standardized procedures and physiological endpoints. Chemosphere 165, 442–452. https://doi.org/10.1016/j.chemosphere.2016.09.053.

Soares, C., Branco-Neves, S., de Sousa, A., Azenha, M., Cunha, A., Pereira, R., Fidalgo, F., 2018. SiO$_2$ nanomaterial as a tool to improve *Hordeum vulgare* L. tolerance to nano-NiO stress. Sci. Total Environ. 622, 517–525. https://doi.org/10.1016/j.scitotenv.2017.12.002.

Spormann, S., Sousa, F., Oliveira, F., Ferreira, V., Teixeira, B., Pereira, C., et al., 2022. Ascorbate supplementation: a blessing in disguise for tomato seedlings exposed to nio nanoparticles. Agric. For. 12 (10), 1546. https://doi.org/10.3390/agriculture12101546.

Sreekanth, T.V.M., Nagajyothi, P.C., Lee, K.D., Prasad, T.N.V.K.V., 2013. Occurrence, physiological responses and toxicity of nickel in plants. Int. J. Environ. Sci. Technol. 10, 1129–1140. https://doi.org/10.1007/s13762-013-0245-9.

Stampoulis, D., Sinha, S.K., White, J.C., 2009. Assay-dependent phytotoxicity of nanoparticles to plants. Environ. Sci. Technol. 43 (24), 9473–9479. https://doi.org/10.1021/es901695c.

Tailor, G., Chaudhary, J., Jandu, S., Mehta, C., Yadav, M., Verma, D., 2023. A review on plant extract based route for synthesis of nickel nanoparticles: biological and photocatalytic applications. Results Chem., 101195 https://doi.org/10.1016/j.rechem.2023.101195.

Taş, R., Köroğlu, E., Celebioğlu, H.U., 2021. Green synthesis of nickel nanoparticles using *Peumus boldus* koch. Extract and antibacterial activity. IJIEA 5 (2), 152–155. https://doi.org/10.46460/ijiea.929625.

Tombuloglu, H., Slimani, Y., Tombuloglu, G., Almessiere, M., Baykal, A., Ercan, I., Sozeri, H., 2019. Tracking of NiFe$_2$O$_4$ nanoparticles in barley (*Hordeum vulgare* L.) and their impact on plant growth, biomass, pigmentation, catalase activity, and mineral uptake. Environ. Nanotechnol. Monit. Manag. 11, 100223 https://doi.org/10.1016/j.enmm.2019.100223.

Tombuloglu, G., Slimani, Y., Tombuloglu, H., et al., 2024. Impact of sonication time in nanoparticle synthesis on the nutrition and growth of wheat (*Triticum aestivum* L.) plant. Plant Nano Biol 8, 100075. https://doi.org/10.1016/j.plana.2024.100075.

Uddin, S., Safdar, L.B., Anwar, S., Iqbal, J., Laila, S., Abbasi, B.A., et al., 2021a. Green synthesis of nickel oxide nanoparticles from *Berberis balochistanica* stem for investigating bioactivities. Molecules 26 (6), 1548. https://doi.org/10.3390/molecules26061548.

Uddin, S., Safdar, L.B., Iqbal, J., Yaseen, T., Laila, S., Anwar, S., et al., 2021b. Green synthesis of nickel oxide nanoparticles using leaf extract of *Berberis balochistanica*: characterization, and diverse biological applications. Microsc. Res. Tech. 84 (9), 2004–2016. https://doi.org/10.1002/jemt.23756.

Wood, B.W., Reilly, C.C., 2007. Interaction of nickel and plant disease. In: Datnoff, L.E., Elmer, W.H., Huber, D.M. (Eds.), Mineral Nutrition and Plant Disease. American Phytopathological Society Press, Minneapolis, MN, pp. 217–247.

Yan, A., Chen, Z., 2018. Detection methods of nanoparticles in plant tissues. New visions in plant science 19, 99. https://doi.org/10.5772/intechopen.74101.

Yan, A., Chen, Z., 2019. Impacts of silver nanoparticles on plants: a focus on the phytotoxicity and underlying mechanism. Int. J. Mol. Sci. 20 (5), 1003. https://doi.org/10.3390/ijms20051003.

Yin, L., Cheng, Y., Espinasse, B., Colman, B.P., Auffan, M., Wiesner, M., et al., 2011. More than the ions: the effects of silver nanoparticles on *Lolium multiflorum*. Environ. Sci. Technol. 45 (6), 2360–2367. https://doi.org/10.1021/es103995x.

Zhao, B., Luo, Z., Zhang, H., Zhang, H., 2022. Imaging tools for plant nanobiotechnology. Front. Genome, 1029944. https://doi.org/10.3389/fgeed.2022.1029944.

Zhou, P., Jiang, Y., Adeel, M., Shakoor, N., Zhao, W., Liu, Y., et al., 2023. Nickel oxide nanoparticles improve soybean yield and enhance nitrogen assimilation. Environ. Sci. Technol. 57 (19), 7547–7558. https://doi.org/10.1021/acs.est.3c00959.

Zulfiqar, F., Navarro, M., Ashraf, M., Akram, N.A., Munné-Bosch, S., 2019. Nanofertilizer use for sustainable agriculture: advantages and limitations. Plant Sci. 289, 110270 https://doi.org/10.1016/j.plantsci.2019.110270.