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Role of Nickel in plants: a review

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Abstract

Nickel (Ni) is the furthermost known indispensable micronutrient for optimum growth and physiological functioning in higher plants. Although required in trace amounts—generally less than 0.5 mg kg{ ¹ of dry biomass—Ni is vital for various metabolic and developmental processes. Due to its very low yet vital concentration, it is often mentioned to as a "nano-nutrient." Functioning primarily as a component of metalloenzymes, nickel is crucial for the activation of key enzymes such as urease and glyoxalase I. It is intricately involved in nitrogen metabolism, seed germination, photosynthesis, antioxidant defence mechanisms, and other specialized physiological pathways. Nickel is particularly vivacious for the hydrolysis of urea-based nitrogen via urease and for alleviating abiotic and oxidative stresses through the glyoxalase (Gly) and glutathione (GSH) detoxification cycles. Furthermore, the limited bioavailability of Ni constrains urease synthesis in plants which can significantly reduce the emission of nitrogen-based pollutants such as nitrous oxide and nitrites. This review critically examines the environmental availability (in soil), physiological significance, enzymatic functions, and systemic impacts of Ni on plants.

Key words : Nickel; essentiality, stress, urease, oxidative stress.

Nickel (Ni) is a transition metal found in Group VIII (d-block) and the fourth period of the periodic table. It is classified as a borderline element among transition metals, with an atomic number of 28, an atomic mass of 58.69 amu, and a specific gravity of 8.902[21]. Discovered in 1751 by A.F. Cronstedt from the mineral "kupfernickel," commonly referred to as gersdorffite, nickel is one of the Earth's primary elements. In terms of crustal abundance, nickel ranks fifth, following iron (Fe), magnesium (Mg), oxygen (O), and silicon (Si)[9]. Nickel can exist in several oxidation states, which include −1, +1, +2, +3, and +4 (Cotton *et al.*,)[6], with the divalent state (Ni^{2+}) being the most biologically active and significant in plant systems[19]. Nickel has a solid, tough, cubic crystal structure that features a distinct silvery-white appearance. It is recognized for its malleability, ductility, excellent resistance to corrosion, and ferromagnetic properties at temperatures below 345°C. In 2001, Liu[27] highlighted that nickel was officially acknowledged as the seventeenth element necessary for plant nutrition, with its essential role confirmed in the late 20th century. Groundbreaking studies conducted by Brown et al. during the 1980s showed that nickel is crucial for the growth and metabolic processes of both monocots and dicots. This concluded in its official recognition as an essential nutrient for plants by the American Association of Plant Food Control Officials in 2004.

Essentiality :

Nickel is crucial for plant physiology as it acts as a cofactor in numerous nickel-dependent metalloenzymes. The urease enzyme, which is well-studied, catalyzes the breakdown of urea into ammonia—a vital process for nitrogen assimilation necessary for plant growth and development[8,12,35]. Moreover, nickel is involved in activating the glyoxalase system, which plays a role in detoxifying methylglyoxal, a harmful byproduct of metabolic activities induced by stress[13].

The significance of nickel in agriculture was first acknowledged in 1945, when Roach and Barclay[37] observed that supplementing nickel in the micronutrient-deficient, acidic sandy soils of the Romney Marshes in England led to higher yields of potatoes, beans, and wheat[38]. In addition to its known function in nitrogen metabolism, nickel has been shown to enhance nitrogen-use efficiency (NUE), which can lessen reliance on synthetic nitrogen fertilizers[27]. This characteristic is particularly important for sustainable agriculture, where it is critical to find a balance between environmental responsibility and maintaining high crop yields. Recent studies also suggest that nickel may improve plant resilience to abiotic stresses, such as drought and extreme temperatures, by promoting the activity of antioxidant enzymes[33]. This stress-mitigating role positions nickel as a promising micronutrient in improving plant adaptability under climate variability and environmental stress conditions[13].

Nickel concentration in Soils :

The overall concentration of nickel (Ni) in soils generally varies from 5 to 500 mg kg{ ^{1}, with an average close to 50 mg kg^{-1} (Hemantranjan)[19]. Nevertheless, much higher levels—between 24,000 and 53,000 mg kg^{-1} —have been observed in dried biosolids (processed sewage sludge) and soils adjacent to metal smelters or refineries. Agricultural soils typically have Ni levels ranging from 3 to 1,000 mg kg^{-1}, influenced by soil composition and management methods.

For plants, the bioavailable form of nickel is Ni^{2+} , crucial for its absorption and use. However, the overall concentration of Ni alone is not a reliable indicator of its bioavailability. Nickel ions (Ni^{2+}) easily oxidize and become trapped in the soil, especially in high-pH environments, making them unavailable to plant roots. Numerous additional elements also affect Ni bioavailability in soil: 1. Soil pH: Increased pH levels reduce the solubility of nickel and its uptake by plants; 2. competition for micronutrients: High concentrations of zinc (Zn) and copper (Cu) can lead to Ni deficiency, since these metals utilize the same uptake route; and 3. Excessive liming: Applying too much lime raises soil pH and may restrict Ni^{2+} availability, resulting in deficiency symptoms. Grasping these dynamics is essential for managing Ni nutrition in crops, particularly in areas where alterations in soil pH or interactions with micronutrients can influence overall plant health and yield[20].

Role of Nickel in plant growth and development :

Nickel (Ni) significantly influences a wide range of physiological and biochemical processes in plants, affecting the structure and function of biomolecules, cellular membranes, organelles, the cell wall, and ultimately, cell division and tissue development. These impacts collectively contribute to overall plant growth, development, and the accumulation of organic matter.

Numerous studies have confirmed that Ni modulates macromolecular structures, particularly nucleic acids. At lower concentrations, Ni has been shown to increase the content of DNA, stabilize its structure, and promote ribosomal stability[22]. The incorporation of phosphorus into nucleic acids, which plays a critical role in plant metabolism, is also Ni-sensitive. In young maize leaves, a low Ni concentration (1 $\mu g\ L^{-1}$) significantly enhanced ^{32}P incorporation into nucleic acids, while a high concentration (104 $\mu g\ L^{-1}$) inhibited it [22].

Nickel alters biomembrane properties and cell wall composition Ni may also serve as a cofactor in the biosynthesis of lignin, which is a structural element of the cell wall[41]. A deficiency in Ni can lead to a decrease in lignin production, thereby weakening cell wall integrity and reducing resistance to pathogens. Enhanced enzyme activity and lignification under Ni influence have been linked to increased resistance to infections[10]. Nickel preferentially binds to cell wall components such as carboxyl groups, hydroxycinnamic acids, and polygalacturonic acids, particularly in root tissues, making the cell wall a key site for Ni sequestration and tolerance[29].

Role of nickel on physiological processes:

a. *Photosynthesis :*

Photosynthesis is indirectly supported by nickel through its regulatory role in nitrogen metabolism and cellular redox homeostasis. The deficiency of nickel can negatively impact photosynthesis by disorganizing chloroplast ultrastructure, impairing chlorophyll biosynthesis, and/or other biochemical processes. These disruptions collectively reduce stomatal conductance and carbon assimilation, ultimately diminishing photosynthetic efficiency and plant productivity[3,34,38]. Reduced chlorophyll content under Ni stress diminishes light absorption efficiency in chloroplasts, directly lowering photosynthetic performance[24]. Ni-induced chlorosis has also been attributed to antagonistic interactions with iron and magnesium, further impairing chlorophyll biosynthesis[26,39].

b. *Nitrogen metabolism :*

Besides serving as a structural element of urease, nickel has a versatile function in the nitrogen metabolism of plants. Numerous Ni-dependent proteins play roles in nitrogen uptake and stress responses. The buildup of free amino acids, especially proline, is a typical reaction to Ni and various heavy metals. Nickel influences nitrate absorption indirectly by altering H^+ -ATPase function and the H^+ / NO_3^- symporter, hindering proton transport and nutrient absorption.

Nickel stress can disrupt nitrogen metabolism in pecan (*Carya illinoinensis*) by affecting the metabolism of ureides, amino acids, and organic acids, leading to the buildup of nitrogenous intermediates like xanthine, allantoic acid, ureidoglycolate, and citrulline, while reducing total ureides, urea levels, and urease activity[2]. Nickel availability also influenced the distribution of free amino acids, with deficiency increasing glycine, valine, isoleucine, tyrosine, tryptophan, and arginine, and decreasing histidine and glutamic acid content. Finally, Ni plays a key role in biological nitrogen fixation, particularly by influencing hydrogenase activity in root nodules. Efficient nitrogen fixation in legumes is closely linked to Ni availability, making it a crucial micronutrient in symbiotic nitrogen metabolism.

c. *Enzyme activation :*

Nickel (Ni) acts as a crucial catalytic cofactor for numerous important metalloenzymes that participate in essential metabolic and physiological functions in plants. These consist of urease, glyoxalase I, peptide deformylases, methyl-coenzyme M reductase, superoxide dismutase, and hydrogenase. Among these, urease is the most extensively studied nickel-dependent enzyme. It promotes the breakdown of urea into ammonium ions (NH_4^+), thus enhancing effective nitrogen uptake. Without nickel, urease stays inactive, causing a buildup of unmetabolized urea to harmful levels in plant tissues.

In pecan trees, a favorable correlation was observed between leaf Ni concentrations and urease activity[32]. Likewise, Oliveira *et al.* (2013) showed that the urease activity in lettuce leaves rose with Ni supplementation, independent of the nitrogen source (urea or ammonium nitrate). In addition to its catalytic function in nitrogen metabolism, urease also demonstrates non-enzymatic biological activities, such as participation in cell-to-cell communication and plant defense. It has demonstrated properties that are both insecticidal and fungicidal, and it has been linked to the nodulation of soybean roots[14].

Urease is crucial in converting urea in agricultural soils, affecting nitrogen behavior in solid and liquid fertilizers and leading to nitrogen losses through ammonia volatilization. Significantly, nickel often builds up in the leaves of plants. In research conducted by Eskew *et al.*[12], leguminous plants grown in nutrient solutions containing urea as the nitrogen source exhibited necrotic lesions at the leaf tips—symptoms linked to Ni deficiency and the resultant accumulation of unmetabolized urea. Analogous findings in cowpea—presenting as chlorosis and necrotic tips—reinforce the critical function of Ni in nitrogen metabolism. Supplementation with nickel has demonstrated the ability to boost leaf urease activity, avert urea-induced toxicity, and facilitate nitrogen recycling via pathways that include the biosynthesis of amino acids, polyamines, and compounds that contain nitrogen[16,17].

Recent studies emphasize Ni's involvement in the detoxification of methylglyoxal (MG)—a toxic byproduct of glycolysis and photosynthesis that builds up during stress. Glyoxalase I (Gly I), an enzyme dependent on Ni, aids in the detoxification of MG through the use of reduced glutathione (GSH), thus maintaining cellular redox balance[23]. Increased MG levels diminish antioxidant defenses, enhance reactive oxygen species (ROS) generation, and suppress cell division[28,36]. Nickel helps reduce oxidative stress by preserving GSH levels and controlling MG concentrations[13]. Additionally, nickel plays an essential role in biological nitrogen fixation in legumes, acting as a cofactor for enzymes that participate in symbiotic relationships with rhizobia.

d. *Seed germination :*

Seed germination and initial seedling growth are vital stages in a plant's life cycle, greatly affecting later growth, yield, and biomass production. The importance of nickel (Ni) during these early developmental phases has been acknowledged for almost a century. Niethammer[31] was one of the earliest to observe that low levels of Ni salts (for instance, 0.1% solutions) had a positive influence on seed germination, while greater concentrations (0.5% to 1.0%) were detrimental. Shweti *et al*.[40] found that low concentrations of $NiCl^-$, (5 mg L^{-1}) positively influenced seed germination and the biomass of seedlings (both fresh and dry weight) in nine different wheat cultivars.

Later research by Mishra & Kar[30] and Das *et al*.[7] validated the beneficial effect of low Ni levels on the germination of different plant species. In a significant long-term study, Brown *et al*.[4] showed that barley plants grown in nutrient solutions lacking Ni for three generations resulted in grain with significantly reduced germination rates. In comparison, seeds from plants cultivated with 1.0 μM Ni showed a germination rate of 94%. These results indicate that Ni is crucial for the formation of viable seeds, likely because of its important function in metabolic processes throughout embryo development. Sufficient Ni levels disrupt the functioning of important hydrolytic enzymes—like amylases, proteases, and ribonucleases—that are crucial for the degradation and utilization of stored resources during germination[1].

Furthermore, the diminished viability of Ni-deficient seeds cannot be recovered through post-harvest Ni treatment, emphasizing the importance of the micronutrient in seed development[4].

The participation of Ni in seed germination is closely associated with its function as a cofactor in urease, an enzyme essential for the release of stored nitrogen compounds during germination. The use of urease inhibitors like phenyl phosphorodia-midate (PPD) has been demonstrated to decrease seed viability. Moreover, necrotic leaf symptoms resulting from urea buildup have been noted in plants grown from Ni-deficient seeds[5]. In contrast, soybean plants grown from seeds enhanced with Ni showed better growth and no indications of urea toxicity[24].

Antioxidant defence mechanism :

Nickel might play a role in controlling the antioxidative defense system, particularly in abiotic stress scenarios[3,15,33]. By facilitating glyoxalase I activation (as outlined previously) and possibly aiding enzymes like superoxide dismutase (SOD), Ni contributes to reducing oxidative harm from reactive oxygen species (ROS), thereby improving plant resilience.

Nickel (Ni) is an essential micronutrient required for the successful completion of the plant life cycle. It lack disrupts essential physiological processes, ultimately stunting plant growth and development. This acknowledgment resulted in Ni being formally categorized as a crucial element for higher plants. Nonetheless, the necessity for Ni differs among plant species, influenced by their metabolic needs and environmental factors.

Experimental findings indicate that both a lack of Ni and its excess (nickel stress) can greatly impact plant physiology. However, field-scale nickel deficiency is quite uncommon since most agricultural soils have adequate plant-available Ni. When a deficiency arises, it can be efficiently remedied by using nickel-rich nutrient solutions or foliar sprays that have diluted nickel salts.

The use of Ni fertilizers has demonstrated favorable results, especially by boosting the function of Ni-reliant enzymes like urease. This enhances nitrogen metabolism, lessens urea toxicity, boosts nitrogen-use efficiency, and decreases the release of nitrogen-related greenhouse gases (*e.g.*, nitrous oxide). Furthermore, progress in the comprehension of Ni-dependent metalloenzymes—particularly glyoxalase I and II, alongside the glutathione (GSH) antioxidant system—has emphasized Ni's essential role in boosting plant resilience to drought, heat, and oxidative stress. These results highlight the possibility of Ni supplementation to enhance sustainable farming and climate-resilient crop yields.

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