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ROLE, TOXICITY AND REMEDIATION OF NICKEL IN PLANTS: A REVIEW

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Abstract

Heavy metals are a group of elements known for their high atomic weight and density, typically over 5 g/cm³. While some, like nickel [Ni], iron [Fe], and zinc [Zn], are essential for plant growth in small amounts, others such as cadmium [Cd], mercury [Hg], and lead [Pb] are purely toxic. Nickel is unique as it plays a dual role in plants. In tiny amounts, it's crucial for healthy development, helping enzymes function properly and aiding in nitrogen metabolism. But when plants absorb in excess, it becomes harmful. It disrupts essential processes like photosynthesis, damages enzymes, and weakens cell structure and stunts overall plant growth. Nickel pollution can be caused naturally, but human activities like industrial manufacturing, burning fossil fuels, and overuse of chemical fertilizers are also major contributors. Due to its harmful effects, especially at high levels, it is considered both as an environmental pollutant and a cancer-causing agent [Group I carcinogen]. Plants take up nickel through their roots and the rate of absorption depends on several factors, such as soil pH, the form of nickel present, and the plant species. Over time, nickel builds up, in the leaves, shoots, and even the tiny pores [stomata] on leaves leading to symptoms like yellowing [chlorosis], dead patches [necrosis], and an imbalance in nutrients. High nickel levels can also trigger oxidative stress by generating reactive oxygen species [ROS], which further harms the plant. Scientists have developed various clean-up methods to deal with Ni pollution, which include traditional approaches, like soil washing or chemical treatment, which can be expensive and disruptive to the environment. Therefore, biological strategies are gaining attention. One of the most promising involves, plant growth-promoting bacteria [PGPBs]. These beneficial microbes not only help plants grow better but also make them more tolerant to heavy metals. This can be achieved by producing helpful compounds like hormones and antioxidants, and by binding and breaking down nickel to reduce its toxicity.

Keywords: Heavy metals, Nickel toxicity, plant metabolism, phyto-accumulation, bioremediation, plant growth promoting bacteria.

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Introduction

Group of heterogenous elements having a specific weight of more than 5g/cm³ [1] and those which vary in their functions and chemical properties are termed as heavy metals. In periodic table, they belong to transition elements. These heavy metals [HMs] can be either essential [Molybdenum-Mo; Manganese-Mn, Copper-Co, Nickel-Ni, Iron-Fe, Zinc-Zn] or non-essential [Cadmium-Cd, Arsenic-As, Mercury-Hg, Lead-Pb]. Most of the HMs act as

co-factors required for enzyme activity, show ductility, conductivity and provide cation stability [2]. However, if these HMs are present in concentrations more than required, they cause toxicity. HM pollutants restrict the growth of plants by affecting their germination, growth, physiological and biological changes etc., [3].

Ni is one such essential minor element required for the development of plants, but, its higher concentration leads to toxicity. Therefore, it is categorised as heavy metal. It is responsible for proper growth and development of plants and plays a key role in morphological and physiological functions at low concentrations of 0.05-10mg/kg dry weight [4]. Conversely, higher concentrations of Ni alters the metabolic activities of plant by inhibiting enzymatic activities, photosynthetic electron transport chain and chlorophyll synthesis [5]. It is a ferromagnetic element ranked as 24th most abundant element on earth's crust. It belongs to VIII group and 4th period of periodic table with

an atomic number of 28 and atomic weight of 58. It shows variable oxidation states spanning from -1 to +4, with +2 as the most stable oxidation state. Physically it appears as a silvery white metal. It can exist in both soluble and insoluble forms [6]. In the environment, the insoluble forms include oxides, sulphides and silicate minerals, while the soluble forms include sulphates of Ni [7]. It is an essential nutrient for few microorganisms, plants and animal species [8]. Most of the enzymes in Archaea, bacteria, algae, primitive eukaryotes and plants require Ni as co-factor [9-13]. Enzymes that require Ni are urease, methyl co-enzyme-M reductase, hydrogenase, acetyl Co.A synthase, Carbon monoxide dehydrogenase, Ni-superoxide dismutase, glyoxylase I and cis-trans isomerase [14-17]. Other known Ni dependent enzymes are glycerol-1-phosphate dehydrogenase from *Bacillus subtilis* and quercitinase from species of *Streptomyces* [18, 19]. The active site of Ni dependent enzymes is coordinated by amino acids Histidine and Cysteine with the assistance from Aspartate and Glutamate [9]. The threshold value of Ni ranges from 30-300mg/kg [20]. Finnish regulations are generally used in international assessments on soil contamination by metals. The limit values they indicate are resulted from years of discussion and are considered most representatives [21]. Threshold value of Ni is 50mg/kg, while the value that presents ecological risk in agricultural land is 100mg/Kg [22].

This review brings together current insights into how nickel affects plants, the dangers it poses, and the latest eco-friendly techniques to manage and remediate its impact-moving us closer to safer agriculture and a cleaner environment.

Nickel Pollution-Causes

Any material that affects the growth and lifespan of living organisms is a pollutant and HMs are considered as environmental pollutants [23, 24]. Nickel, a naturally abundant element, is emitted into the atmosphere naturally and by anthropogenic activities which at higher concentrations is toxic and affects life; therefore, it is an environmental pollutant [25]. It is let into the environment by wind, weathering of rocks and wildfire. It is one of the HMs classified as a group I carcinogen [26]. Permissible limit of Ni in soil is 35mg/kg, in water it is 0.02mg/l; above which, it causes toxicity to all living beings [27-29].

Natural Sources of Nickel

Naturally, it is released into the atmosphere from windblown sand, windblown from rocks and soil, volcanic activity, wild forest fires, sea salt spray, marine and continental volatiles, and aerosols from oceanic dust [30]. Into the aquatic environment, nickel enters through weathering, dissolution and atmospheric evaporation of nickel rich rocks and soils. It is present on clay particles as soluble salts and organic matter or as soluble salts of humic acid and fulvic acid. Primary bed rock minerals are dissolved due to rain water and the surface of the water bodies get contaminated. The mobility of nickel in soil is more after acid rains, due to which its concentration in

groundwater is increased [31]. Depending on the factors such as soil type, pH, sampling depth etc., surface water and underground water contain active nickel [32]. It is also released into the soil due to atmospheric emissions.

Anthropogenic activities

Certain activities of humans, release nickel into the atmosphere as sulphides, oxides, silicate soluble compounds and even as metallic nickel. It is primarily released into the atmosphere as aerosols [17, 33]. About 0.04 - 0.58µg nickel is released from cigarette, due to which, smoking 40 cigarettes per day may cause a human to inhale 2 - 23µg of nickel [34]. Due to lubricants from inefficient vehicles, nickel is emitted during transportation. Industrial processes like mining, smelting, industrial waste water and effluents, as well as domestic waste water also contains nickel. Approximately 0.5 - 2 ppb of nickel is present in seawater, while rivers contain about 0 - 23ppb of nickel [35]. Acceptable limit of nickel in drinking water is 20 µg/L, according to the Bureau of Indian Standards [BIS 2012] Central water commission, [36]. Industries that are responsible for Ni pollution are, electroplating, industrial dust, production of iron and steel, food processing industries, chemical industries, fertilizers, industrial aerosols, mining and metallurgy, battery and combustion of coal [37]. Combustion of fossil fuels and application of chemical fertilizers also contribute to the anthropogenic activity of Ni to the environment [38]. Major source of atmospheric Ni is, fossil fuel where, it exists mostly as Nickel oxide, Nickel sulphate and oxides of complex Nickel containing metals [39]. Metal manufacturing waste, commercial waste, sludge coal fly ash, coal bottom ash also contributes to the anthropogenic sources of nickel to the environment. This excess accumulation of nickel in the environment causes problems in agricultural soils which may be due to diminished soil liming and acid rain for industrialisation [40].

Essentiality of Nickel in Plants

Nickel was considered as an essential metal for plant growth in 1987 [41]. It is essential for plant metabolism but, is dangerous or toxic when present in higher concentrations [42]. It is an essential micro element that is required for the normal growth and development of plant and is responsible for several biological functions [43]. Minute concentrations of nickel is essential for optimum plant growth and development [44]. When applied at a minimum concentration of 10 µm, improved plant growth and increased accumulation of biomass was observed [45, 46]. Improvement in plant height, number of branches and accumulation of biomass was observed in *Hibiscus sabdariffa* seedling when 20mg of nickel was applied for 1kg soil [20mg/kg] [47]. Improvement in plant growth and development might be due to Ni, required for optimum functioning of enzymes such as urease and hydrogenase metabolism [48]. It plays an important role in activation of several biological processes [49, 50]. Essentiality of nickel was first verified by Eskew *et*

al.,[1983][51] in soyabean plant and it was confirmed that it is an essential plant micronutrient. When *Hordeum vulgare*[L.] plants were grown in Ni depleted controlled conditions, they were not able to produce viable seeds for three successive generations [41]. For enzymes like glyoxylase - I and urease, which are required for nitrogen metabolism in higher plants, Ni is an integral part [52]. It also has a significant role to play in the growth of seedlings and development. Possible mechanism for this could be requirement of Ni for optimum functioning of enzymes like urease and hydrogenase [53]. It is also vital for RNase activity [54]. Reports have been documented on essentiality of nickel in nitrogen cycle [55-58]. Application of Nickel, increased biomass accumulation, when grown in adequate supply of urea; while its deficiency, reduced urease activity in leaves and roots of the plant [59]. Adequate supply of Ni has enhanced the activity of Nitrogen reductase in onion [60], tomato [61] and cucumber [62]. Treating the seeds with Ni before sowing, showed an increase in the activity of urease in soyabean [63] and the grains had high content of nickel which correlated with increased remobilisation of nitrogen from older to younger leaves [64, 65]. Bertrand and De wolf [1973][66] believed that nickel plays a crucial role in biological nitrogen fixation. Application of nickel increased nodule formation and urease activity in soyabean [67]. Further, when the concentration of nickel was increased from 0.1 to 10 mg/kg in soil, the percentage accumulation of nickel was 42 to 50 and urease activity was 20 to 30 in shoots and leaves of soyabean [67]. Nickel is an integral part of [Ni-Fe] hydrogenase, an enzyme that plays an important role in recycling of hydrogen, an obligatory product in Nitrogen reduction [68]. Ni being an essential trace element, is responsible for iron uptake and seed germination, while in excess, gets accumulated in seeds, buds and fruits. It also interferes with leaf area and plant height, prevents lateral roots from growing, breaks photosynthesis machinery and slows down root cell division during mitosis [69]. Therefore, Ni is an essential trace element for plants and an integral part of several enzymes which is required for many physiological and biochemical processes.

Uptake of Nickel and Transportation in Plants

Nickel is taken up by the roots of the plants by active transport and passive diffusion [44]. But, the ratio of active to passive diffusion varies with species and concentration of nickel in soil solution [70]. From the roots, nickel is transported to shoot and leaves [71] through xylem [72]. It can also be translocated to fruits and seeds through phloem [73]. This depends on different factors like, form of Ni, plant species, concentration of Ni in the soil, pH of soil, metabolism of plant and organic contents in soil [74]. Availability of nickel in plants is related to its concentration in soil solution, soil pH, organic matter and iron manganese contents [75]. It is more soluble and mobile in acidic soils [low soil pH], therefore symptoms of nickel toxicity are clearly visible in

plants grown on acidic soils [76]. It has the ability to form complexes with colloidal particles of soil, hence can be exchanged easily with crystal lattices of different nutrients in solid phase [77]. Once the plants take up the available form of nickel, it is mostly accumulated in roots and then translocated to other parts of the plant [78]. Nickel ions uptake in plants, is regulated by amino acids. They act as chelators forming complexes with Ni ions and enhance Ni uptake in plants [79]. It was also reported that, exogenous application of amino acids to wheat plants improves Ni ratio from symplast to apoplast [79]. Once Ni is taken up, it is distributed in the aerial parts of the plant and it finally gets accumulated in cellular parts [80]. It is redistributed to shoots, leaves and other parts of the plant through phloem [81]. Ni accumulation is seen more in shoot when compared to roots and maximum accumulation is seen in stomatal guard cells of leaves [82]. Less amount of Ni is accumulated in seeds [83].

Nickel Toxicity in Plants

Nickel, being an essential micronutrient for plants is responsible for cellular redox reactions, plant growth and development. However, beyond the permissible limit, it alters the functions of many cellular components, which may result in cellular damage and finally death of the plant. High concentration of Ni in plants have shown to reduce vegetative growth [84]. Accumulation of nickel in excess, i.e., beyond permissible limit, causes disruption of iron uptake and metabolism that results in chlorosis and necrosis in plants [85,86]. It inhibits, modifies or enhances the activity of a large number of target molecules. Transition elements can cause toxicity in plants by removing or blocking essential components from biomolecules and by changing their structure and function [87]. Reports also suggested that, Ni stress has an effect on ultrastructure of leaf, thickness of mesophyll cells, size of vascular bundles, diameter of vessels and width of leaf epidermal cell of wheat [44]. It inhibits root and shoot growth and interrupts cell division due to which leaf area decreases [88]. Nickel toxicity hampers the anatomy and morphology of plant by decreasing the vascular bundle size, mesophyll thickness and plasticity of the cell wall [89] which ultimately disturbs seed germination and other metabolic processes [44]. This has an impact on photosynthesis either by altering or displacing the metal ion magnesium and hindering the activity of chlorophyll. It can also affect by disrupting chloroplast structure, interferes with electron transport chain, hinders enzymatic activities and decreases photosynthetic pigments [90]. In *Brassica oleraceae*, higher concentration of Ni, decreased volume of intercellular spaces, palisade and mesophyll cells [91]. Higher concentration of Ni in soil, altered various physiological processes in plants and exhibited symptoms as chlorosis and necrosis [92]. Ni toxicity also causes membrane functionality disruption and ion imbalance in cytoplasm [93] has also been reported that water relations such as osmosis and diffusion, leaf water potential, stomatal conductance,

transpiration rate leading to reduced water intake [94] and total moisture content were disturbed under Ni stress [95]. Seregin and Ivanov (2001)[96], have observed that, Ni induced disorders may affect the structure and activities of cell membrane enzymes, which could lead to reduced nutrient uptake. Studies have suggested that Ni toxicity also affects ion balance in numerous plant organs [97]. Plants when exposed to Ni stress experienced ion leakage [98], loss of osmolytes and decrease in cell turgor pressure due to which membrane permeability decreases leading to leakage of essential ions through cell membrane [44,99]. Higher concentrations of Ni leads to oxidative damage of plant organelles due to production of ROS [Reactive Oxygen Species] including H_2O_2 , O^{2-} and OH [100, 101]. Ability of plants to cope with oxidative stress is characterised by antioxidant activity [102, 103]. Chlorophyll content in leaves was decreased due to Ni stress and causes chlorosis due to depletion of Mg^{2+} and Fe^{2+} , which ultimately affects chlorophyll production [104].

Effect of Nickel Toxicity on Various plant parameters

On Plant Growth and Development

The essentiality of metal ions for plant growth, depends on their concentration in plants and environment [102]. Inhibition of cell growth induced by nickel is related to inhibited cell division [90]. Seeds, when in direct contact with nickel show varied germination. Nickel toxicity substantially inhibit seed germination [105]. 20% of seed germination was reduced in pigeon pea under nickel toxicity [106]. 2.0mM of nickel, was found to reduce the germination of many seedlings when compared to control in *Zea mays* [107]. Shoot biomass of wheat was found to decrease by 20% and 26% when 100mM and 200 mM of nickel was applied [108]. Similarly, seedling growth and seed germination of *Brassica juncea* was reduced considerably [109]. Concentrations of nickel varying from 10-100mg/L reduced root growth, development and growth of pepper seedlings [110]. Root and plant growth were found to be inhibited when *Nicotiana tabacum* plants were exposed to nickel at a rate of 0.43 mM [111]. Significant retardation in subsequent growth of seedlings were observed when cabbage plants were exposed to 0.5 mM nickel for 8 to 10 days [112]. Root growth is majorly affected rather than shoot growth due to nickel toxicity [113]. Lateral roots in rice and maize were reduced, as nickel enters into endodermal cells and is accumulated in pericycle cells [114]. Root growth was reduced by 37 to 53% respectively, when wheat seedlings were treated with 100 and 200mM nickel [108]. Root architecture system of tomato was damaged due to nickel toxicity [115].

On Nutrient uptake

Plants under nickel stress showed decreased concentrations of many nutrients like Fe, Cu, Zn, Mg and Mn [116]. Due to this decrease in absorption of nutrients under nickel toxicity, plants become nutrient deficient

[117, 118, 119]. Calcium ions are removed from the binding sites of oxygen evolving complex [120] and replaces magnesium ions in chlorophyll [121]. Under these circumstances in pigment system II, electron transport is inhibited which reduces the supply of energy for the uptake of nutrients. Conversely, at higher concentrations of nickel the intake of calcium by rice plants increases to avoid its hazardous effect [122]. Grain production is considerably reduced, as nickel toxicity inhibits translocation of Cu, Mn and Mg [123]. Decrease in nutrient concentration leads to poor growth reduction in physiological functions, chlorophyll formation, decrease in enzyme activity that controls photosynthesis and transpiration, lower biomass production and ultimately lowers the yield [124, 125]. Deficiency of magnesium is caused due to nickel stress, which leads to deterioration of chlorophyll and ultimately resulting in leaf chlorosis and necrosis [125].

On Carbohydrate metabolism, Photosynthesis and its pigments

The concentrations of reducing and non-reducing sugars in sunflower cultivation were reduced as nickel effected α -amylase activity [126]. Primary energy source for photosynthesis is chlorophyll [127], but the net photosynthetic rate and chlorophyll content were decreased in *Brassica juncea* under nickel toxicity [128]. Ni and vanadium toxicity reduced gaseous exchange elements in watermelon and tomato [129, 130]. Photosynthetic pigments chlorophyll a, b and carotenoids were effected due to nickel toxicity [44] leading to necrosis and chlorosis [46]. At high concentrations, nickel demolishes epidermal and mesophyll cells [131], deteriorates grana structure, thylakoid membranes [132] and decreases the size of grana [133] ultimately resulting in reduction of photosynthetic pigments [134]. Excess amount of nickel reduces chlorophyll contents which reduces photosynthesis in plants [135, 136]. By imposing a concentration of 0.025 mM nickel, chlorophyll contents were reduced approximately by 47% [137]. If the concentration was increased from 20 - 100 μ M of nickel, chlorophyll a and b contents were reduced by 70 and 50% respectively [138]. When wheat plants were exposed to various concentrations of nickel like 0, 25 and 50 g/L, it was observed that chlorophyll contents were reduced with increasing concentrations [139]. Photosynthetic efficiency of lettuce plants was significantly reduced at higher concentrations of nickel [140]. Conductance of stomata [116], photosynthesis [141] transpirational rate and water use efficiency in different plant species [142] were found to be reduced due to nickel toxicity. It also causes photo inhibition in pigment system II [143], inhibits the enzymes of Calvin cycle, increases stomatal closure, thereby induces carbon dioxide deficiency and ultimately leads to reduction in photosynthesis [144]. It reduces the photosynthetic rate by affecting the enzyme activities of aldolase, phosphoglyceraldehyde dehydrogenase, RuBisCO, 3-phospho glycerate kinase and fructose 1,6-bis phosphatase. Production of these enzymes leads to

accumulation of ATP and NADPH, creating higher pH gradient across the thylakoid membranes, thereby blocking the activities of pigment system II [116].

On Nitrogen Metabolism

Nickel stress increases the production of ROS, which damages proteins [46]. Nickel binds to functional groups of proteins like -SH groups and modify their structure which considerably reduces the activities of the enzymes that contain -SH groups [44]. Any metals stress causes the accumulation of different amino acids in plant cells which leads to reduction of total protein [145]. Experiments conducted and studied on *Stackhousia tryonii* by Bhatia et al.,[2005][146] showed the amino acid profile in xylem sap. It was observed that, nickel stress caused reduction of amino acids by 22% and accumulation of Glycine by 48%. However amino acids asparagine and glutamine were increased. Significant correlation was reported between nickel toxicity and accumulation of glutathione and cysteine [147]. Plant tolerance under nickel stress was increased due to increase in amino acid accumulation. In hyper accumulating plants, accumulation of an acid is a primary occurrence under nickel stress which substantially detoxifies it [149].

On enzyme activity

Antioxidative defence system and redox balance plays a key role in limiting ROS production and mitigating oxidative stress under abiotic stress. The activities of antioxidant enzymes like SOD, CAT, APX, GR, GST and POD were improved under excessive nickel concentration [110]. The activities of SOD, GR and POD enzymes were improved under nickel toxicity [98]. Heavy metal ion toxicity impacts the formation of free oxygen radicals which results in increasing the enzymatic activity [150]. This was observed in tomato [151] soyabean [152] and in zucchini seeds [153] all under nickel toxicity. These antioxidant enzymes scavenge ROS and other free radicals and protect the cell membrane from damage.

Remediation Strategies for Nickel Toxicity

Though nickel is an essential micro element for plants, higher concentration causes toxicity which hampers plant growth and productivity. Hence it is essential to minimise its hazardous effects on ecosystem by various strategies. Several investigations are in progress to minimise the entry of Ni into the environment and thereby into the ecosystem. Many remediation approaches are available, which have their own merits and demerits. They can be summarised as:

Physico-Chemical remediation

These methods include immobilising of nickel, soil replacement, soil washing, encapsulation. They detoxify the soils by trapping free metal cations.

Immobilisation

This method aims to immobilise the metal by using certain immobilising agents that include chelants such as citric acid, and EDTA; chemical additives such as zeolite, phosphate, hydroxyapatite [HA] and biochar [154]. These substances decrease the mobility of metals by

precipitation, complexation and absorption. Zeolitic materials have high porosity sorption capacity and pH, making them ideal for metal immobilisation [155]. On the other hand, phosphate fixes by precipitation, absorption and by rhizosphere effect [156]. The effective and promising material to immobilise heavy metals in soil is biochar. This immobilises metals by physical adsorption, surface co-precipitation and surface or inner complexation with functional groups. Addition of biochar to soil may increase soil pH, water holding capacity, soil fertility and reduces the mobility of plant-available pollutant and promotes re-vegetation [157]. The alkaline surface of biochar delays the time to reach hazardous pH by altering acid neutralising capacity [158]. The high electric charge on the surface of biochar absorbs metal cation and detoxifies the soil. Therefore, biochar's ability to reduce metal concentration by adsorption, precipitation and complexation reduced the phytotoxicity of nickel [159]. The comparative effectivity of various chelants for nickel was in the order of EDTA greater than citric acid greater than histidine [160].

Soil Washing

Methods where, washing agents like acids, hydroxy chelating agents or surfactants are used to immobilise free Ni is known as soil washing. Poly glutamic acid was used as washing agent [161] to remove Ni from soil. Others, which can be used to remove Ni by soil washing are citric acid, acetic acid, EDTA, HCl. A good rate of Ni removal from soil was achieved by surfactant enhanced soil washing [SESW][162]. The factors that affect or influence soil washing are, soil properties, acid solution type and reaction time on acid washing [163].

Electro Remediation

In this method, the Ni contaminated soil is inserted with two electrodes and current is applied to create an electric field. Under the influence of electric field, metals mobilise and gather at high pH electrode. For electro kinetic remediation, electrolyte solutions are required which will desorb Ni and help it move towards cathode [164]. Efficiency of electro-remediation is affected by current density, type of electrolyte and other conditions which arise during the process. By the addition of humic acid and fulvic acid as chelating agents in cathode, Ni removal efficiency was 2-3 times higher than the un-enhanced electro-remediation [165]. Ni removal efficiency can be further enhanced by chelates such as nitrilotriacetic acid [NTA], diethyl triamine penta acetic acid [DTPA] and diaminocyclo hexane tetra acetic acid [DCyTA]. Limitations for the above approaches are; 1.]Is not cost effective; 2.] requires more labour 3.]occurrence of irreversible changes in soil properties and 4.] disturbance in native soilmicroflora. When chemical methods are employed for Ni decontamination, other secondary problems arise, which can be overcome other approaches.

Bioremediation

Biological methods are being used to decrease the amount of heavy metals in environment which has attracted the attention of researchers. Plants, bacteria, fungi and algae

are usually used in this method which is known as bioremediation. This is eco-friendly, cost effective and non-invasive. This can be broadly categorised as phytoremediation and microbial remediation.

Phytoremediation

An appealing eco-friendly method of remediation is phytoremediation which involves application of Ni absorbing hyper accumulator plants. Basing on the modality of application, this is further of different types. Uptake of contamination from soil and water by plant roots is phytoextraction [166]. Removal of pollutants from contaminated waste water by plants is phytofiltration [167]. The usage of plants for stabilisation of contaminants by reducing the mobility of pollutants and preventing their entry into food chain is phytostabilisation [168]. Destruction of organic xenobiotics by plant enzymes like oxygenases and dehalogenases is phytodegradation [169]. Usage of halophyte plants to remove sodium chloride from salt affected soils and to enable them for normal plant growth is phytodesalination [170, 171]. Heavy metals are extracted from soil by cropping them with hyper accumulating plants which can concentrate these metals in the aerial parts of plants. These plants are harvested, dried and smelted. This process allows the metal to recover from the plant and is known as phytomining [172]. Plants which can accumulate more than 1000mg Ni/kg of dry weight in their shoots when grown under natural habit are known as hyper accumulators. *Alyssum bertolonii* contained 10mg/g of Ni in dry matter. This was observed by Minguzzi and Vergnano in 1948. *Pycnanandra acuminata*, an endemic tree in New Caledonia, has the ability to accumulate Ni in its latex of blue green colour [173]. Herbaceous crops such as barley, bean, cabbage, ricinus, sorghum, spinach and tomato has the ability to phytoremediate Ni polluted soils [174]. When leaves, roots, stem and fruits were separately collected from these plants, oven dried and analysed, it was found that spinach, cabbage and ricinus stored Ni in leaves while bean, barely and tomato showed higher concentration of Ni in leaves and in stems. Spinach has been most efficient in removal of Ni as it contains highest levels of metal per gram of dry matter with respect to other herbaceous crops [174]. For phytoremediation of Ni from metal enriched soils, Ni hyper accumulator *Alyssum murale* has been developed as a commercial crop [175]. *Phyllanthus balgooyi*, *Phyllanthus securinegioides* and *Rinorea bengalensis* showed bioaccumulation and distribution of Ni. Study showed that Ni is mainly concentrated in roots and stems of all these three plants [176]. However, *Phyllanthus balgooyi* has highest Ni concentration in the leaves of phloem among these three. After four months of standard inorganic treatment, leaves and stem of *A. murale* contained 3600mg/kg Ni. Plants which accumulate more than 10,000 mg Ni/kg are, *Psychotria douarres* and *Geissois pruinosa* and these plants are known as hypernickelophores [177]. High levels of Ni were observed in the leaves of *Rinorea niccolifera* by using colorimetric reagent dimethyl glyoxime [178, 179].

Further analysis of this plant tissue revealed foliar Ni concentrations varying from 7168 to 18,388mg/kg on dry weight basis. This plant is also categorised as hyper nickleophore as it surpassed 10,000 mg/kg Ni accumulation in leaves. Therefore, these plants can be effectively used as phytoremediants.

Plant growth promoting rhizobacteria influences plant growth and development in two ways a.] by increasing phytohormone and siderophore levels and b.] by decreasing the harmful effects of plant pathogenic organisms. When plants are inoculated with plant growth promoting rhizobacteria, they improve metal tolerance and promote higher Ni accumulation [180]. Studies by Babu *et al.*, [2013][181] and Kamran *et al.*, [2016][182] showed that inoculants increased the quantities of ACC deaminase and IAA in Ni hyper accumulators and these in turn enhanced Ni extraction in contaminated soils. The two phytohormones that contribute to plant growth are IAA and ethylene, however high concentration of ethylene is barrier for roots. Ethylene can be hydrolysed by ACC deaminase produced by mutual reactions of plant and bacteria which promote production of more plant biomass that help for removal of Ni. *Arthobacter nicotinovorans* SA40 was able to promote plant growth and phytoextract Ni from soil [183]. Other bacteria with beneficial effect against Ni phyto toxicity is *Bacillus subtilis* strain SJ-101 [184]. PGPR increase Ni uptake in hyperaccumulators [185]. Under Ni stress, these PGPR increase root-shoot length, their dry biomass, root girth, total chlorophyll and nitrogen content.

Microbial remediation

Apart from phytoremediation, researchers were attracted by microbial remediation to decrease the amount of heavy metals in the environment. Microbes are used to remove heavy metals from soil by various techniques like biosorption, bioleaching, bioaugmentation and biofiltration. Bacteria and algae can remove Ni by biosorption [186]. Through oxidation reduction reactions of microbial metabolism, metals are removed by bioleaching. Biostimulation and mineralisation are other mechanisms to treat metal pollution. Biomineralisation is another frequently used method controlled by biological organic matter, crystal formation and external environment. It transfers free cations into sediment through the precipitation of cells, metabolites and macromolecules. In this process, heavy metals are bound and precipitates are formed for the removal of metals. Another method relevant to biomineralisation is microbial induced carbonate precipitate [MICP], critical is ureolytical microbes. Hydrolysis of urea forms ammonium $[NH_4^+]$ ion and carbonate $[CO_3^{2-}]$ ion which leads to increase in environmental pH and metal cation precipitation with carbonate. Therefore, for MICP process, isolation of bacteria and fungi that secrete urease is essential [187, 188]. Hence, activity of urease is controlling factor in MICP process that influences metal removal [188]. To precipitate heavy metals by MICP technology, optimal environmental

conditions are required [189]. Among most of the microbial remediation methods, MICP is the latest technology being used in treating Ni contaminated soils. Further, certain Ni degrading bacteria, like *Bacillus cereus* and other species of *Bacillus* were isolated [190, 191] and using these bacteria with MICP technology yielded better results.

Conclusion

Though an essential micronutrient, Ni becomes highly toxic to plants when in excess, disrupting physiological, biological and structural processes. It makes a significant focus in agricultural and environmental research owing to its dual role as a vital enzymatic co-factor and potent environmental pollutant. Rapid industrialisation, fossil fuel combustion and excessive fertilizer usage have amplified Ni contamination in ecosystems, leading to its accumulation in plant tissues and subsequent impairment of growth, metabolism and yield. Remediation techniques can come to the rescue of its contamination with biological approach, in particular by using PGPBs offering sustainable and eco-friendly alternative. These microbes enhance plant tolerance to Ni toxicity by modulating hormonal balance, improving nutrient uptake and reducing oxidative stress through antioxidant enzyme activity and metal chelation.

This review highlights the importance to understand Nickel's dual nature and advocates for the continued development and implementation of biologically based remediation strategies. By integrating advanced microbial approaches with agricultural practices, it is possible to mitigate Ni toxicity, promote healthier crop production and move towards more resilient and sustainable future of agriculture.

Author Contributions

All authors are contributed equally

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Declaration of Competing Interest

The Authors have no Conflicts of Interest to Declare.

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