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Nickel availability, deficiency and toxicity in soils and plants: A review

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Abstract

Nickel plays many important roles in the growth and development of plants. Its deficiency or toxicity symptoms can occur when it is present in too little or too much amount, respectively. Its status in soils is highly dependent on the nickel concentration of the parent rocks, but in surface soils, its content depends on soil-forming processes. Total Ni content in soils varied widely from 3.0 to 1000 mg kg^{-1} and depends on the soil types. Total Ni content in soil positively correlates with the clay and organic matter content and negatively correlates with the fine sand content. Although it is present in various forms in soils, the most readily available form to plants is the Ni^{-2+} ion. The availability of Ni depends on several physicochemical properties of soils. The magnitude of available Ni was reported to be higher in the lowlands than in the uplands. Its availability is greater in surface soils than in subsurface soils. High concentrations of Ni in plants adversely affect their growth and development. The toxicity levels of Ni vary widely and depend on plant species.

Keywords: Nickel, total, available, critical concentration, toxicity, soil, plant

Introduction

Nickel is a metallic element and stands in the 28th position in the periodic Table. It is a silver-white metal found in several oxidation states however, the +2-oxidation state (Ni $^{2+}$) is the most common one in biological systems (Denkhans and Salnikow, 2002) [28]. Nickel is an essential micronutrient that is required for optimal plant growth and development. It is a vital element for several animal species, microorganisms, and plants, and therefore either deficiency or toxicity symptoms can occur when too little or too much Ni is taken up, respectively. Dixon *et al*. (1975) [30] reported that nickel is a component of plant urease. A tissue culture study showed that soybean (*Glycine max* Merr.) cells could not grow in the absence of Ni when provided with urea as the sole nitrogen source (Polacco, 1977) [80]. Subsequently, many researchers reported that plant growth is severely influenced by nickel deficiency when urea is the sole nitrogen source (Eskew *et al*., 1983; Gerendas and Sattelmacher, 1999) [23, 39]. Brown *et al*. (1987) [18] have demonstrated that Ni is an essential micronutrient for barley, which failed to complete its life cycle in the absence of Ni, and that the addition of Ni to the growth medium completely alleviated its deficiency symptoms. Nickel has been demonstrated to be associated with urease from Jack bean (*Canavalia ensiformis*) seeds (Dixon *et al*. 1980a) [31]. This enzyme catalyzes the hydrolytic cleavage of urea to ammonia and carbon dioxide and is widely distributed in higher plants (Welch, 1981) [11].

Nickel status in soils is highly dependent on the Ni content of the parent materials, which reflects on the soil-forming process and pollution (Ali *et al*., 2009) [1]. The mobility and bioavailability of Ni in the soil and its distribution and transformation in the solid phase are influenced by various soil properties such as soil texture, pH, organic matter, and Fe-Mn oxides (Ma and Rao, 1997; Barman *et al*., 2013) [105, 13]. To understand the availability of nickel in soils and its deficiency and toxicity in plants, it is necessary to review the availability, deficiency and toxicity of nickel to understand the soil and plant conditions under which nickel it may occur.

Occurrence

Nickel (Ni) is the 24th most abundant element in the earth's crust, accounting for about 3% of its composition. It is the fifth most abundant element by weight after iron, oxygen magnesium, and silicon. It is a member of the transition series and belongs to group VIII B of the periodic Table. In nature, Ni occurs in various mineral forms. It is a member of the transition metal series. It is resistant to corrosion by air, water, and alkali, but dissolves readily in dilute oxidizing acids. Although it can exist in several different oxidation states state under environmental conditions, the most popular oxidation state is $Ni2^+$ ion.

Among the trace metals, it is widely distributed in the environment, being released from both natural sources and anthropogenic activity, with input from both stationary and mobile sources (Cempel and Nikel, 2006) [22]. It is present in air, water, soil, and biological material. Natural sources of nickel are wind-blown dust, derived from the weathering of rocks and soils, volcanic emissions, forest fires, and vegetation. Phosphoric fertilizers, mud combustion, mining activities, the combustion of diesel fuel, coal, and fuel oil, the incineration of waste and sewage, and miscellaneous sources are among the anthropogenic factors playing a role in the release of Ni into nature (Clayton and Clayton, 1994; Grandjean, 1984; Spectrum, 1998) [26, 41, 95].

Nickel in soils

Generally, nickel is distributed uniformly throughout the soil profile but typically accumulates at the surface due to the deposition of industrial and agricultural activities. The most significant nickel ore types are pentlandite, nickel-iron sulfate, garnierite, and nickel magnesium silicate. Its status in soils is highly dependent on the nickel concentration of the parent rocks, but in surface soils, its content is also a reflection of soil-forming processes and pollution (Kabata-Pendias and Pendias, 1992; McGrath, 1995) [49, 66]. The sedimentary rocks that include clays, limestones, sandstones, and shales contain the lowest contents of Ni, while the highest concentrations of Ni exist in basic igneous rocks (Kabata-Pendias and Mukherjee, 2007) [47]. The mean content of Ni in various types of rocks is shown in Table 1.

Table 1: Mean nickel (mg kg^{-1}) content in different types of rocks (Mielke, 1979) [67]

S. No.	Type of rock	Ni content
1	Ultramafic igneous	2000
2	Basaltic igneous	140
3	Shales and Clays	68
4	Black Shales	50
5	Limestone	20
6	Granitic igneous	8
7	Sandstone	2

Total Ni content in soils

Nickel content in soils varied widely from 3.0 to 1000 mg kg^{-1}. The range of Ni in the world's soils was from 0.2 mg kg^{-1} to 450 mg kg^{-1}, while the mean was 22.0 mg kg^{-1} (Kabata-Pendias and Pendias, 1992; Cempel and Nikel, 2006; Bencko, 1983; Scott-Fordsmand, 1997) [49, 22, 15, 89]. An average concentration of 86.0 mg kg^{-1} for the natural nickel content in the earth's crust was also reported by Duke (1980) [33]. Serpentine soils are especially known for their high Ni contents (Mizuno *et al*., 2018) [70]. Soils formed on serpentine materials contain Ni from 100 to 7000 mg kg^{-1}. Based on a review of many published papers worldwide, the average concentration of Ni in the soil is 93 mg kg $^{-1}$ (Bogdanovic *et al*., 1997) [17]. Nickel concentration in the soil depends on the soil type to a large extent. Values representing the contaminated level of Ni in rural soils of the world for various countries have been reported by Chen *et al.* (1999) [24]; Australia (60 mg kg^{-1}), Canada (150 mg kg^{-1}), China (20 mg kg^{-1}), France (50 mg kg^{-1}), Germany (200 mg kg^{-1}), Japan (100 mg kg^{-1}), the Netherlands (210 mg kg^{-1}), South Africa (15 mg kg^{-1}), United Kingdom (60 mg kg-1) and the United States of America (420 mg kg^{-1}). However, Shacklette and Boerngen (1984) [93], in their soil survey of the USA, reported a Ni concentration range of less than 5 to 700 mg kg^{-1}, with a geometric mean of 13±2.31 mg kg^{-1}. Alloway (1990) [2] reported that the normal range of Ni in soils is 2.0 to 750 mg kg^{-1}. Rawat *et al.* (2019) [86] studied the total Ni content in soils of various agroclimatic zones of Jharkhand state, India (Table 2), and found that the mean content of total Ni in the lowland soils was higher than in the midland, followed by the upland, because of clay percentage and organic matter content that influenced their status. Total Ni content in the soil positively correlates with the content of clay and organic matter and negatively correlates with the fine sand content. Badawy *et al.* (2022) [10] reported the total Ni content in Egyptian soils ranged from 14.2 to 48.3 mg kg^{-1} with an average of 31.4±8.02 mg kg^{-1} in the surface layers and from 9.5 to 45.5 mg kg^{-1} with an average of 27.5±7.15 mg kg^{-1} in the subsurface layers. Okoli *et al.* (2020) [73] and Wang *et al.* (2015) [99] reported that the Ni in soil surface layers was higher than the subsurface layers due to the organic matter content, soil pH, and parent materials.

Table 2: Total Ni (mg kg^{-1}) content in soils of different agro-climatic zones of Jharkhand, India (Rawat *et al.*, 2019) [86]

Agro-climatic zone	Topography	Range	Mean
IV zone, Central & North eastern plateau	Upland	147-297	200.84
	Midland	291-371	307.16
	Lowland	351-472	419.12
V zone, Western plateau	Upland	122-156	141.32
	Midland	167-347	263.56
	Lowland	253-486	348.88
VI zone, South eastern plateau	Upland	93-297	173012
	Midland	219-367	275.20
	Lowland	421-630	528.92

Available Ni content in soils

The most available form of Ni for plants is Ni^{2+} ions under anaerobic conditions (Cempel and Nikel, 2006) [22]. In soil solution, Ni is predominantly found in a hydrated ion [Ni (H$_2$O)$_6^{2+}$] form (Yusuf *et al*., 2011) [102]. It is the major source of Ni in soil solutions, which is taken up by plants and microorganisms. Nickel is relatively stable in an aqueous solution. In soil solution, Ni may exist as a complex with inorganic and organic ligands and/or be associated with suspended mineral colloids, where the organic complexes may be dominant. Nickel can also exist in several forms in soils, including adsorbed or complex on organic cation surfaces or on inorganic cation exchange surfaces, inorganic crystalline minerals or precipitates, water-soluble, free ion or chelated metal complexes in soil solution (EHC, 1991; Bennett, 1982) [34, 16]. In the presence of humus, particularly fulvic and humic acids, the complexes are much more mobile and may be more significant than the hydrated divalent cation in soil solution (ATSDR, 2005) [7]. The available Ni content in soil depends on soil type, pH, cation exchange capacity of the soil, its topography, presence of other metal ions (Fe, Cu, Mn, Zn, etc.), CaCO$_3$ content of the soil, and organic matter content. The available Ni status in the soils of four districts of Uttar Pradesh (India) was reported by Singh and Patra (2020) [94] (Table 3). Similarly, Rawat *et al*. (2019) [86] also reported available Ni content in soils of various agroclimatic zones of Jharkhand, India (Table 4). Due to soil drainage and clay content, the lowlands contain a higher amount of available Ni than the midlands followed by the uplands (Anderson and Christensen, 1988) [5]. The concentration of DTPA extractable Ni in the surface soil layers (0.85 to 4.0 mg kg-^{1}) was higher than that in the subsurface layers (0.77 to 3.08 mg kg^{-1}) in Egyptian soils (Badawy *et al*., 2022) [10]. A higher concentration of available Ni in surface soils than in subsurface soils may be due to the organic matter content and pH.

Critical concentration of Ni in soils

The critical limit of deficiency of DTPA extractable Ni in soil for soybean was 0.17 mg kg $^{-1}$ (Barman *et al*., 2020) [13], and for spinach, it was 0.46 mg kg $^{-1}$ (Kumar *et al*., 2021) [57]. Nickel deficiency is more common in dry and cold soils in the early stages of plant development. Wood (2006) [101] reported that it can be induced by the presence of higher concentrations of Zn, Fe, Mn, Mg, Ca, and Cu and root damage by nematodes.

Table 3: Available Ni (mg kg $^{-1}$) content in soils of various districts of Uttar Pradesh, India (Singh and Patra, 2020) [94]

District	Available Ni content	
	Range	Average
Varansi	0.03-20.88	1.87
Mirzapur	0.01-8.71	1.30
Sant Ravidas Nagar	0.01-3.31	0.99
Chandauli	0.01-3.73	0.94

Table 4: Available Ni (mg kg $^{-1}$) content in soils of various agro-climatic zones of Jharkhand (Rawat *et al*., 2019) [86]

Agro-climatic zone	Upland		Midland		Lowland	
	Range	average	Range	average	Range	average
IV zone, Central & North eastern plateau	0.06-2.08	0.83	0.06-2.5	1.08	0.38-1.54	0.59
V zone, Western plateau	0.06-0.68	0.20	0.06-1.48	0.64	0.52-2.20	0.87
VI zone, South eastern plateau	0.76-3.1	1.58	0.06-3.42	1.54	0.84-4.46	1.35

The solubility and thus the mobility and availability of Ni for plants increase with decreasing pH and decreasing ion exchange capacity of the soil. Hence, soil pH is the major factor controlling Ni solubility, mobility, and sorption, with clay content, iron-manganese minerals, and soil organic matter being of secondary importance (Anderson and Christensen, 1988; Ge *et al*., 2000; Suava *et al*., 2000; Tye *et al*., 2004) [5, 69, 97].

Nickel content in plants

Nickel is an essential micronutrient required for the growth of higher plants (Brown *et al*., 1987) [18]. The plants readily take up Ni from the soil, and up to a definite Ni concentration in plant tissues, it is positively correlated with the soil Ni content (Kabata-Pendias and Pendias, 2000) [48]. The phytoavailability of Ni has been correlated with free Ni ion activity in soil solution; hence, plant uptake is also dependent on soil pH, organic matter content, and iron-manganese oxide (Massoura *et al*., 2006; Rooney *et al*., 2007; Ge *et al*., 2000) [64, 87, 38]. The uptake of Ni by plants depends on various soil properties, mainly on its form and concentration in the soil, the presence of other metals, the composition of organic matter, and plant metabolism (Chen *et al*., 2009) [24]. A higher pH value in the soil solution reduces the Ni uptake because of poorly soluble Ni complexes are formed. Nickel is necessary for the majority of higher plants in very low concentrations. The normal concentration range of Ni in most plant tissue is between 0.1 and 1.0 mg kg^{-1} (Marschner, 1995) [62]. However, Brown *et al*. (1987) [18]; Bryson *et al*. (2014) [21]; and Fabiano *et al*. (2015) [36] reported that the normal range of Ni concentration in most plant tissues is from 0.05 to 5.0 mg kg^{-1} on dry weight, and a concentration above this range induces toxicity to plants (Yusuf *et al*., 2011) [102]. Badawy *et al*. (2022) [10] recorded that the concentration of Ni in the rice straw ranged from 1.33 to 2.58 mg kg^{-1} with an average of 2.12±0.28 mg kg^{-1}, and from 0.26 to 0.58 mg kg^{-1} with an average of 0.44±0.06 mg kg^{-1} in rice grain, while, Ni in the wheat straw ranged from 1.06 to 2.22 mg kg^{-1} with an average of 1.69±0.27 mg kg^{-1} and from 0.19 to 0.35 mg kg^{-1} with an average of 0.28±0.04 mg kg^{-1} in wheat grain. They also found a positive correlation between the available Ni in the soil and the straw and grain Ni concentrations in both rice and wheat crops.

Functions of nickel in plants

Nickel is an important metal in plant metabolism and a co-factor of many metalloenzymes (Drzewiecka *et al*., 2012) [32]. It is recognized to be the most important Ni metalloenzyme in higher plants (Polacco *et al*., 2013). Urease has two types of properties, namely catalytic and non-catalytic, as well as a structure and catalytic mechanism (Mazzei *et al*., 2020) [65]. The role of Ni in urease function was demarcated by Dixon *et al*. (1975) [30]. Urease is present in the seeds of various families, especially in the Cucurbitaceae, Fabaceae, Asteraceae, and Pinaceae (Bailey and Boulter, 1971) [11]. Urease is also present in the tissues of the leaves of all plants to a lesser extent (Hogan *et al*., 1983) [45], which allows the volatilization of ammonia from the surface of plants. Ureases are ubiquitous metalloenzymes that catalyze the transformation of urea. Marschner (2012) [63] reported that urease consists of six subunits, each containing two Ni atoms. Gerendas and Sttelmacher (1999) [39] and Gajewska and Sklodowska (2009) [37] reported that Ni plays a significant role in the metabolism of plants. In conditions of Ni deficiency, urease activity decreases the urea concentration in the top of leaves, which can reach 2.5% in dry matter, causing tissue necrosis. Its deficiency reduces the activity of urease and other enzymes involved in nitrogen metabolism, like nitrate reductase. So, it adversely affects protein synthesis and total nitrogen content (Brown *et al*., 1990) [20].

In nonenzymatic, biological properties, it shows a role in cell-to-cell communication. Plant urease has insecticidal and fungicidal effects, and plays a role in soybean nodulation. Jack bean urease indicates interaction with cell membrane lipids.

Urease plays an important role in varied metabolic processes, including ureolysis, hydrogen metabolism, methane biogenesis, and acetogenesis (Mulrooney and Hausinger, 2003) [72]. A small amount of Ni increases the growth and yield of plants and is also essential for the biosynthesis of anthocyanins (Ragsdale, 1988; Lopez and Magnitskiy, 1983) [84, 59]. Ureta *et al*. (2005) [98] and Zobiole *et al*. (2009) [104] found that Ni deficiency reduced the symbiotic hydrogenase activity in *Rhizobium leguminosarum*, which may directly affect the symbiotic N_2 fixation.

Critical concentrations of Ni in plants

The concentration of a nutrient in plants below which a deficiency is likely to occur. The critical value of a nutrient indicates the soil or tissue content below which a plant is most likely deficient in that specific nutrient and whose production could be enhanced by the addition of the nutrient. The critical concentration of Ni deficiency for soybean was 0.20 mg kg^{-1} (Barman *et al*., 2020) [13], and for spinach, it was 2.20 mg kg^{-1} (Kumar *et al*., 2021) [57].

Deficiency symptoms of Ni in plants

Nickel deficiency symptoms first appear on the older leaves of the plants because Ni is mobile in plants. Wood *et al*. (2006) [101] described in detail the symptoms of Ni deficiency in certain organs of woody plants. The leaves are characterized by the following: Chlorosis, reduced size, and altered shape, a transitory dark green zone at the leaf tip, tip necrosis, cupping and wrinkling of leaves, the absence of laminar development, and a winged petiole. Shoot and root characteristics include: Loss of apical dominance and resetting, internodes and tree size are increasingly diminished, buds shapes tend to become increasingly distorted; bud break tends to be delayed, the shoots and limbs are noticeably brittle, the root systems are reduced. In reproduction organs, a small percentage of flowers will develop and ripen. In soybeans, the lack of Ni due to reduced urease activity leads to the accumulation of toxic urea concentrations in the leaves (Eskew *et al*., 1983) [23]. In tomatoes, the young leaves are chlorotic, and the meristem necrotizes (Checkai *et al*., 1986) [23]. In conditions of Ni deficiency, barely germinating grains form due to the disturbed process of grain filling. Therefore, it is barely not able to complete its life cycle in the absence of Ni, while its application eliminates the symptoms of deficiency (Brown *et al*., 1987) [18]. Due to Ni deficiency nodulation is delayed and N fixation efficiency is reduced in legume plants. Therefore, for leguminous crops such as green beans and cowpea, Ni fertilization might be needed, particularly for those soils with high Zn or Cu concentrations, or pH > 6.7 (Brown 2006) [19]. In Ni deficiency, pecan plant leaves show “mouse-ear" symptoms.

Toxicity and toxicity symptoms of Ni in plants

A high concentration of Ni is toxic for both plants and animals, including humans (Ameen *et al*., 2019) [4]. The toxicity index of Ni is different for sensitive and tolerant crop species. It is > 10 mg kg^{-1} in sensitive crop species and > 50 mg kg^{-1} in tolerant crop species (Seregin and Kozhevnikova, 2006; Yusuf *et al*., 2011; Marschner, 2012) [90, 102, 63]. Nickel toxicity levels vary widely between 25 and 50 mg kg^{-1} (Mishra and Kar, 1974) [68]. However, Gregson and Hope (1994) [42] reported that the phytotoxic concentrations of Ni occurred at leaf contents of 10 to 100 mg kg^{-1} depending on the plant species, while, Kabata-Pendias and Pendias (2001) reported a phytotoxic range of 40 to 246 mg kg^{-1} dry weight tissue, depending on the plant species and cultivars. The most common plants that have been identified for their tolerance to and hyperaccumulation of Ni include cabbage, cauliflower, and turnips, as well as legumes such as beans and peas (Kabata-Pendias and Mukherjee, 2007) [47].

Maksimovic *et al*. (2012) [61] reported that high concentrations of Ni can adversely affect the growth, development, and production of dry matter in plants. Those mechanisms include the production of free radicals and oxidative stress, inhibition of enzyme activity and cation and anion uptake, changes in membrane permeability and water relations, declines in photosynthesis and respiration, morphological and anatomical changes, and inhibition of seed germination, growth, and development. These physiological and morphological changes caused by excessive concentrations of Ni are manifested by various symptoms of injury, including chlorosis, necrosis, wilting of leaves, stunted growth, and dry matter production. Corn root became brown after Ni treatment (Baccouch *et al*., 2001) [9]. In the presence of high Ni concentrations, there was a significant decrease in growth and dry matter production in different pea cultivars, in mung bean (Pandey and Pathak, 2006) [74], and in eggplant (Pandey and Gopal, 2010) [75]. However, Pavlova *et al*. (2018) [76] found a decrease in seed germination in Alyssum species. While increasing Ni concentrations in mustard, a greater decrease in dry matter yield in leaves and stem than in root was reported by Gopal and Nautiyal (2012) [40], although Ni accumulation was higher in the root. Sugar beet plants, show chlorotic and necrotic spots on older leaves due to the excess concentration of Ni (29.8 mg kg^{-1} dry matter). Over time, chlorosis turns into necrosis, and necrotic spots spread within the intercostal part of the leaf. Kastori *et al*. (1996) [51] reported that middle-aged leaves turn yellow and wither. Excess Ni also adversely affects the germination process and seedling growth characteristics of plants (Aydinalp and Marinova, 2009; Sethy and Ghosh, 2013) [8, 92]. Ni toxicity can result in inhibited lateral root formation and subsequent development in maize (Seregin *et al*., 2003) [91] and cowpea (Kopittke *et al*., 2007) [55]. The toxicity of Ni appreciably reduced biomass production, root nodulation, and the number of functional nodules in chickpeas at 100 mg kg^{-1} and higher levels of Ni (Khan and Khan, 2010) [53]. Al-Qurainy (2009) [3] also investigated that a high concentration of Ni (150 ug g^{-1}) in soil severely reduced biomass, root and shoot length, plant height, and leaf area in *Phaseolus vulgaris*.

Nickel uptake by plants

Plants can uptake Ni through their roots and above ground organs. Terrestrial plants predominantly uptake Ni through the roots via passive diffusion and active transport. The Ni uptake by plants largely depends on its concentrations in the nutrient medium. Nickel is translocated to all the tissues of the root via both the apoplast and symplast. Soluble Ni compounds can be taken up through the cation transport systems for $Cu^{2+,}$ $Zn^{2+,}$ and Mg^{2+} due to the similarity of the charge/size ratio, especially Ni and Mg ions. Chen *et al.* (2009) [24] reported that secondary, active transport of chelated Ni^{2+} is possible. According to the results achieved through studying the effects of temperature, light intensity, inhibitors of respiration, and anaerobic conditions, it can be concluded that, at least partially, the uptake of Ni depends on metabolic processes (Aachmann and Zasoki, 1987 [6]; Petrovi and Kastori, 1994) [79]. In addition to Ni uptake, plant roots can also release it into the environment, accounting for approximately 5% of the total amount absorbed (Petrović and Kastori, 1979) [78]. Ni can affect the uptake of ions of the other elements by stimulation or inhibition (Petrović *et al*., 2003; Rahman *et al*., 2005; Hasinur *et al*., 2005; De Queiroz Barcelos *et al*., 2017) [77, 85, 44, 27]. Ni uptake appears to be an active process, as it is influenced by temperature, anaerobic conditions, and respiratory inhibitors such as dinitrophenol (Aschmann and Zasoski, 1987) [6]. The Uptake of Ni by plants depends upon various factors, the most important of which is the ionic, Ni concentration in the medium (Dixon *et al*., 1980; Halstead *et al*., 1969; Roth *et al*., 1991) [31, 43, 88]. Soil pH values below 5.6 seem to favor the absorption of Ni and are largely due to the fact that the exchangeable Ni content of the soil increases with increasing soil acidity (Mizuno, 1968) [68]. Halstead *et al*. (1969) [43] and Polacco (1976) [82] found that Ni absorption was increased by increasing the phosphate content of the soil. Foliar spraying with $Co(NO_3)_2$ on tomatoes and cucumbers also increases the Ni content. Peat with high Ni (80 µg g^{-1}) content was unable to supply Ni to barley (*Hordeum vulgare*) seedlings (Morrison *et al*., 1980) [71]. The addition of peat to Ni-rich soil significantly inhibits Ni uptake. This inhibition may be due to the complexing of the soluble Ni with the insoluble forms, competition from other metal ions in the medium, or both. Halstead *et al*. (1969) [43] reported that organic matter present in the soil inhibits the uptake of Ni by plants to some extent. The presence of other divalent cations, as in the case of soybean and barley, in the culture solution also influences the uptake of Ni^{2+} (Klucas *et al*., 1983; Korner *et al*., 1987; Lee *et al*., 1987) [54, 56, 58].

The translocation of Ni in the xylem occurs in various forms, most often in the form of citrate and malate complexes. Nickel can be translocated from the xylem to the phloem as well as redistributed (Zeller and Feller, 1998) [103]. When applying increasing doses of Ni to triticale by introduction to the soil, 70% of the total accumulated amount of Ni was in the grain and only 30% in the vegetative parts of the shoot. Kastori *et al*. (2004) [52] found that the translocation index, describing the translocation of Ni from the vegetative plant parts to the grain, was the highest in Ni among the ten examined microelements. Studies by Banjac *et al*. (2021) [12] indicated a different accumulation of Ni in the seeds of cultivated species. The median concentration of Ni in wheat and maize seeds was 5.0 mg kg^{-1}, while soybean and sunflower seeds had much higher Ni content (8.40 and 10.26 mg kg^{-1}, respectively). Consequently, the seed bio-accumulation factor ranged from 0.013 in maize to 0.256 in soybeans.

Conclusion

It may be concluded that the availability of Ni is greater in surface soils than in subsurface soils. The magnitude of available Ni is greater in the lowlands than in the uplands. The deficiency of Ni in the soil varies from soil to soil. The deficiency of Ni in plants also varies from plant species to species. The toxicity level of Ni in plants depends on their sensitivity and tolerance capacity.

Conflict of 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.

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