Journal of Elementology ISSN 1644-2296

Osalade, A. and Bosiacki, M. (2025)
'Determination of the effect of nickel on the emergence and chemical composition of lettuce seedlings grown in rockwool',
Journal of Elementology, 30(4), 715-729,
available: https://doi.org/10.5601/jelem.2025.30.2.3554

RECEIVED: 15 April 2025
ACCEPTED: 16 October 2025

ORIGINAL PAPER

Determination of the effect of nickel on the emergence and chemical composition of lettuce seedlings grown in rockwool[1]

Abimbola Osalade, Maciej Bosiacki

Department of Plant Physiology
Poznan University of Life Sciences, Poznan, Poland

Abstract

Nickel is a nutrient classified as a microelement, essential for plant growth, responsible for nitrogen metabolism. Research is being conducted worldwide to determine the optimal levels of nickel for the cultivation of many plant species, in various horticultural technologies. One of them is hydroponic cultivation of lettuce on rockwool. In hydroponic lettuce cultivation, the quality of the lettuce seedling is very important. Its nutritional status affects the yield of good quality and quantity. The study aimed to determine the effect of increasing nickel concentrations (increasing doses of nickel: I – control, II – 0.5 mg Ni dm^{-3}, III – 1 mg Ni dm^{-3}, IV – 2.5 mg Ni dm^{-3}, and V – 3.0 mg Ni dm^{-3}) in the nutrient solution on the seedling emergence, fresh mass and chemical composition of butter head lettuce seedlings (*Lactuca sativa* L.) grown in rockwool. The following measurements were taken: number of seedlings emergence per treatment, total fresh mass, chemical composition of leaves: N, P, K, Ca, Mg, Na, Fe, Cu, Zn, Mn, Ni, and the content of heavy metals Cd, Pb, Cr in the aerial parts of the plant. The results of this experiment confirm that application of nickel at a minute level (0.5 mg dm^{-3}) improved the biomass of lettuce seedlings and resulted in obtaining the highest amount of N, Ca, Mg, Na, Fe in lettuce leaves. However, in this concentration, the disadvantageously highest content of the toxic metals cadmium and chromium occurred. We can also conclude that excess of nickel (3.0 mg dm^{-3}) in the nutrient solution creates a strong negative effect on seedling emergence and fresh mass of lettuce seedlings, while also retarding the uptake of most macronutrients and micronutrients required in the plant except nickel, increasing when more nickel is added to the solution.

Keywords: hydroponics, quality and production of lettuce, macronutrients, micronutrients, heavy metals

Maciej Bosiacki, PhD DSc, Prof. UPP, Department of Plant Physiology, Poznan University of Life Sciences, Wołyńska 35, 60-637 Poznan, Poland, e-mail: maciej.bosiacki@up.poznan.pl
* No source of funding.

INTRODUCTION

An alternative to growing lettuce in soil is hydroponics. This is possible with the use of nutrient solutions as an alternative growth substrate with some additional advantages over the use of soil. According to Mandizvidz (2017), hydroponics is currently a widely and frequently used plant cultivation technique. Lettuce is a well-known crop used for various reasons, including its nutritional value. The plant is adaptable to year-round cultivation, all seasons, and a variety of cultural systems, including greenhouses, plastic tunnels and open fields (Draghici et al. 2016). The quality and production of lettuce are influenced by nutrients. As a result, the administration of nutrients in a balanced manner is critical to the product's quality (Domingues et al. 2012). Plant nutrition management has become a critical component of hydroponics production's success.

The regulation of the nutrient concentration is one of the actions conducted as part of this management because the proper nutrient concentration will boost the effectiveness and efficiency of nutrient absorption by plants (Aini et al. 2019).

Nickel has only lately been added to the list of important plant micronutrients (Shivay, Prasad 2019). It is a component of the enzyme urease. It aids in the conversion of urea to ammonia and carbon dioxide (Gajewska et al. 2006, Hussain et al. 2013, Shivay, Prasad 2019). It is now known to play a critical role in a variety of plant physiological activities, like nitrogen metabolism, water relations, germination, photosynthesis, growth, and senescence (Sreekanth et al. 2013, Shivay, Prasad 2019). Most crops benefit from nickel because it increases yield and improves quality. Without Ni, some crops, such as barley (*Hordeum vulgare* L.), cannot complete their life cycle (Amjad et al. 2019).

Additionally, nickel is required by a variety of microorganisms, animals, and plants (Hussain et al. 2013). Nickel is absorbed by plants primarily as an ion (Ni^{2+}), whereas it is far more difficult to absorb as a chelate. Nickel is absorbed by various monocotyledonous plants, such as wheat, rye, and maize, through the root cap (Rathor et al. 2014, Antonkiewicz et al. 2016). Plants with high nickel levels have been shown to slow down metabolic activity and reduce water and nutrient uptake (Singh, Shyam 2011).

However, due to the risk associated with heavy metal uptake and accumulation in leaves in the traditional method of lettuce cultivation in soil (Kleiber et al. 2013), and also considering that nickel is an extremely mobile element that can be readily taken by plants in proportion to its concentration in the soil until it reaches levels lethal to plants (Antonkiewicz et al. 2016). The use of a closed hydroponic system that has a quality nutrient solution will help to prevent plants from accumulating excessive amounts of heavy metals (Kleiber et al. 2013). Consumers around the world are also increasingly interested in having more quality, environmentally friendly, and fresh lettuce and other vegetables, due to a strong and well-established inverse correlation between consumption of healthy greens and reduction of the risk of many types of chronic and degenerative diseases like cancer, cardiovascular disease, and neurological disorders (Aires 2018).

Nickel is classified as a micronutrient, which is necessary for plant growth (Brown et al. 1987). There are no established optimal nickel concentrations for growing specific plant species. For hydroponic cultivation of lettuce on rockwool, the optimal nickel concentration has not been established yet.

In consideration of the foregoing, an experiment was carried out to determine the effect of increasing nickel concentrations in the nutrient solution on the seedling emergence and chemical composition of lettuce seedlings (*Lactuca sativa* L.) grown in rockwool. The aim was to determine the optimal nickel level for the production of lettuce seedlings in rockwool.

The specific objectives are:

– to recognise the effect of increasing nickel concentrations in a nutrient solution on seedling emergence and yield of lettuce.
– to gain knowledge of the effect of increasing nickel concentrations in a nutrient solution on the content of micronutrients, sodium, macronutrients and heavy metals in lettuce.

MATERIALS AND METHODS

Experimental site and conditions

The experiment was carried out at the Experimental Station of the Department of Plant Physiology, Faculty of Agriculture, Horticulture and Biotechnology, Poznan University of Life Sciences Poland.

Planting materials

Seeds of lettuce (*Lactuca sativa* L.) of the cultivar Zeralda (BRP9321) were obtained from the seed company Hazera. A total of 1000 seeds were sown at amounts of 50 seeds per replicate. The sowing day was 18th of May, 2021. The experiment consisted of 5 combinations, each combination consisting of 4 replications. One replication was a rockwool mat in which 50 lettuce seeds were sown.

Field experiment

The greenhouse was equipped with static hydroponics structures (nutrient solution containers to facilitate lettuce cultivation). The temperature throughout the experimental period was between 18°C to 21°C and the relative humidity was between 75- 80%. Seeds were sown in rockwool. Rockwool was saturated with the nutrients 48 hours before sowing. The nutrient solution contained the following elements (mg dm^{-3}): N-ammonium ($N\text{-}NH_4$) <10, nitrogen (N)-nitrate ($N\text{-}NO_3$) 150, phosphorus ($P\text{-}PO_4$) 50, potassium (K) 150, calcium (Ca) 150, magnesium (Mg) 50, iron (Fe) 3.0, manganese (Mn) 0.5, zinc (Zn) 0.54, copper (Cu) 0.03, boron (B 0.011) and with varying concentrations of nickel, and had the following parameters: pH 5.50, electrical conductivity (EC) 1.80 mS cm^{-1}.

The water used to prepare a nutrient solution had a pH of 7.44 and EC of 0.62 mS cm^{-1}, and contained (mg dm^{-3}): $N\text{-}NH_4$ 0.4, $N\text{-}NO_3$ 1.1, $P\text{-}PO_4$ 0.68, K 4.7, Ca 63.5, Mg 14.4, $S\text{-}SO_4$ 56.9, Na 31.2, Cl 35.2, Fe 0.07, B 0.011 Zn 0.54, and trace amounts of Mn, Cu, Mo, and Ni.

Experimental design and treatment

The experiment was carried out in a completely randomized block design with five treatments (increasing doses of nickel: I – control, II – 0,5 mg Ni dm^{-3}, III – 1 mg Ni dm^{-3}, IV – 2.5 mg Ni dm^{-3}, and V – 3.0 mg Ni dm^{-3}).

Chemical analysis

For the chemical analysis of the nutritional status, the aerial parts of plants (after 35 days of cultivation) were taken; they were dried in a temp. range of 45-50°C and then homogenized (Kleiber et al. 2013). For the determination of the total content of N, P, K, Ca, Mg, and Na, the plant material was mineralized in concentrated sulfuric acid (90% H_2SO_4) – Kleiber et al. (2013). After mineralization, the following were determined: N-total – by the Kjeldahl distillation method; P – colourimetrically with ammonium molybdate; K, Ca, Mg, Na – using flame atomic absorption spectroscopy with the FAAS method (on a Carl-Zeiss Jena apparatus).

The lettuce leaves was wet-mineralized in a mixture of ultrapure HNO_3 and pure $HClO_4$ (3:1 v/v) for determination of micronutrients and heavy metals (Bosiacki, Roszyk 2010). The content of Cd, Cr, Cu, Fe, Mn, Ni, Pb and Zn in the plant material was measured by means of flame atomic absorption spectroscopy (FAAS) on an AAS-5 spectrophotometer (Carl-Zeiss Jena apparatus).

Data collection

– Number of emerged seedlings

The number of seedlings that emerged was counted 15 days after sowing.

– Lettuce yield evaluation

Harvesting was done 35 days after sowing, and fresh weight (g for one rockwool mat) was measured upon harvesting by using an electronic weighing balance.

Data analysis

The results were analyzed statistically to determine the number of seedlings emergence, fresh mass of lettuce leaves, content of macronutrients, sodium, micronutrients and heavy metals in lettuce leaves under the influence of increasing nickel concentrations. One-way analysis of variance was used. The differences between the means were determined by Duncan's test at the significance level of α=0.05.

RESULTS

The increasing nickel concentrations significantly influenced the number of lettuce seedlings that emerged (Figure 1). The statistically highest number of emerged lettuce seedlings was obtained in the nutrient solution with a nickel dose of 0.5 mg Ni dm^{-3}. The lowest number of lettuce seedlings that emerged was found in the nutrient solution with 3.0 mg Ni dm^{-3}.

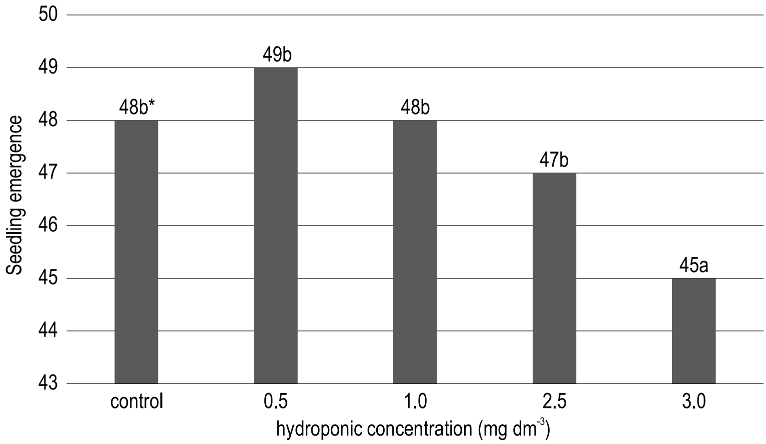

Fig. 1. Effect of increasing nickel concentrations on the mean number of seedling emergence.
* followed by the same letters do not differ significantly at α=0.05

The increasing nickel concentrations significantly influenced the fresh mass of lettuce seedlings (Figure 2). The highest quantity was harvested from lettuce growing in the nutrient solution with a dose of 0.5 mg Ni dm^{-3}, while the lowest one was obtained from lettuce leaves in the nutrient solution with a dose of 3.0 mg Ni dm^{-3}. The fresh mass lettuce weight ranged from 157g to 351g fresh mass per mat.

The increasing nickel concentrations significantly influenced the N content (Table 1). The highest content of nitrogen was found in lettuce leaves growing in the nutrient solution with a dose of 0.5 mg Ni dm^{-3}, while the lowest was in lettuce leaves growing in the nutrient solution with a dose of

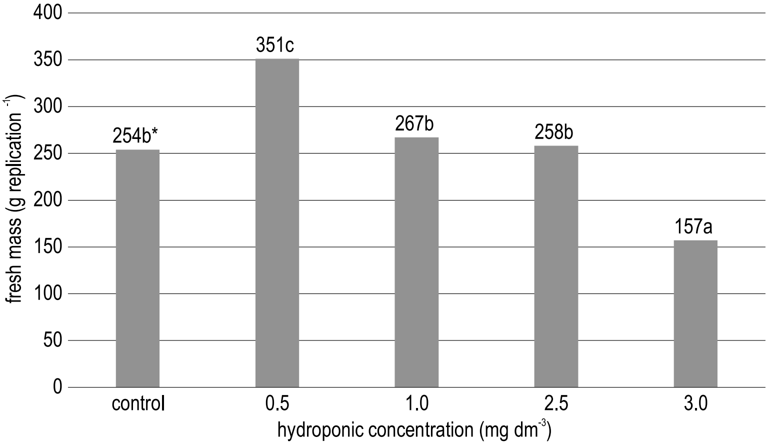

Fig. 2. Effect of increasing nickel concentrations on the fresh mass of lettuce seedlings (g replication^{-1}). * followed by the same letters do not differ significantly at α=0.05

Table 1

Effect of increasing nickel concentrations on the macronutrients and sodium content in lettuce (g kg^{-1} dry mass)

Macronutrient and sodium	Hydroponic concentration mg (Ni dm^{-3})				
	control	0.5	1.0	2.5	3.0
N	35.6 ^{b*}	42.1 ^{c}	34.3 ^{b}	31.1 ^{b}	26.3 ^{a}
P	0.8 ^{a}	0.9 ^{a}	0.9 ^{a}	0.9 ^{a}	0.9 ^{a}
K	68.8 ^{a}	68.7 ^{a}	63.5 ^{a}	59.5 ^{a}	54.2 ^{a}
Ca	9.9 ^{bc}	10.9 ^{c}	9.3 ^{abc}	8.1 ^{ab}	7.1 ^{a}
Mg	6.5 ^{ab}	9.2 ^{b}	6.5 ^{ab}	7.3 ^{ab}	5.1 ^{a}
Na	14.0 ^{ab}	14.9 ^{b}	13.2 ^{ab}	11.7 ^{ab}	10.0 ^{a}

* followed by the same letters do not differ significantly at α=0.05

3.0 mg Ni dm^{-3}. The nitrogen content in lettuce ranged from 26.3 to 42.1% g kg^{-1} of dry mass.

The increasing nickel concentrations in the nutrient solution did not have a significant effect on the phosphorus content in lettuce (Table 1). Lettuce leaves growing in the nutrient solution to which nickel was introduced contained 0.9 P g kg^{-1} of dry mass.

The increasing nickel concentrations in the nutrient solution did not have a significant effect on the potassium content in lettuce (Table 1). Despite statistically insignificant differences in the potassium content in lettuce leaves, a decrease in the amount of K was found under the influence of the increasing nickel concentrations. The potassium content in lettuce ranged from 54.2 to 68.8 g kg^{-1} of dry mass.

The increasing nickel concentrations significantly influenced the Ca content (Table 1). The highest content of Ca was found in lettuce leaves growing in the nutrient solution with a concentation of 0.5 mg Ni dm^{-3}, while the lowest one was in lettuce leaves growing in the nutrient solution with a concentation of 3.0 mg Ni dm^{-3}. The calcium content in lettuce ranged from 7.1 to 10.9 g kg^{-1} of dry mass.

The statistically highest magnesium content in lettuce leaves was obtained in the medium with a nickel concentation of 0.5 mg Ni dm^{-3} (Table 1). The lowest magnesium content was found in the leaves of lettuce growing in the nutrient solution with 3.0 mg Ni dm^{-3}. The magnesium content in lettuce ranged from 5.1 to 9.2 g kg^{-1} of dry mass.

The statistically highest sodium content in lettuce leaves was obtained in the nutrient solution with a nickel concentation of 0.5 mg Ni dm^{-3}. The lowest sodium content was found in the leaves of lettuce growing in the nutrient solution of 3.0 mg Ni dm^{-3}. The sodium content in the lettuce ranged from 10.0 to 14.9 g kg^{-1} of dry mass.

The copper content in the lettuce leaves ranged from 1.24 to 4.62 (mg kg^{-1} dry mass) – Table 2. The studies showed no significant effect of increasing nickel concentration on the copper content in lettuce.

Table 2

Effect of increasing nickel concentrations on the micronutrients (mg kg^{-1} dry mass) content in lettuce

Micronutrient	Hydroponic concentration mg Ni dm^{-3}				
	control	0.5	1.0	2.5	3.0
Cu	3.61 ^{a*}	3.85 ^{a}	3.81 ^{a}	4.62 ^{a}	1.24 ^{a}
Fe	111.28 ^{ab}	161.79 ^{c}	132.67 ^{bc}	100.76 ^{ab}	89.52 ^{a}
Mn	87.78 ^{c}	71.41 ^{bc}	68.27 ^{b}	35.56 ^{a}	42.61 ^{a}
Ni	1.21 ^{a}	9.24 ^{b}	13.87 ^{c}	22.61 ^{d}	34.34 ^{e}
Zn	211.84 ^{b}	188.72 ^{ab}	185.30 ^{ab}	176.63 ^{a}	174.14 ^{a}

* followed by the same letters do not differ significantly at α=0.05

The iron content in the lettuce leaves ranged from 89.52 to 161.79 (mg kg^{-1} dry mass), – Table 2. The highest content of Fe was found in the lettuce growing in the nutrient solution to which 0.5 mg Ni dm^{-3} was added. The lowest Fe content in lettuce leaves was found in plants growing in the nutrient solution at a concentation of 3.0 mg Ni dm^{-3}.

The lowest manganese content in lettuce leaves was found in plants grown in the nutrient solution with a concentation of 2.5 mg Ni dm^{-3} (Table 2). The highest manganese content in lettuce leaves was found in the control lettuce.

The increasing nickel concentrations in the nutrient solution had a significant impact on its content in lettuce leaves. In the control, 1.21 mg kg^{-1} was found, while the content in leaves of plants growing in the nutrient solution with nickel ranged from 9.24 to 34.34 mg kg^{-1}. The increasing nickel concentrations in the nutrient solution resulted in obtaining a lower zinc content in lettuce leaves. The highest content of this micronutrient was obtained in the lettuce from the control (Table 2). The zinc content in the lettuce leaves ranged from 174.14 to 211.84 mg kg^{-1} dry mass.

The cadmium content in the lettuce leaves ranged from 1.11 to 1.70 (mg kg^{-1} dry mass) – Table 3. The highest content of Cd was found in the leaves of plants growing in the nutrient solution at a concentration of 0.5 mg dm^{-3}. The lowest content of Cd was found in the leaves of plants growing in the control nutrient solution.

The increasing doses of nickel had a significant effect on the content of chromium in lettuce leaves (Table 3). The highest content of Cr was found in the leaves of plants growing in the nutrient solution at a concentration of 0.5 mg dm^{-3}. The lowest content of Cr was found in the leaves of plants growing in the nutrient solution at a concentration of 3.0 mg dm^{-3}.

No statistically significant differences were found in the lead content in the lettuce leaves due to the increasing nickel content in the nutrient solution. The lead content in the lettuce leaves ranged from 3.89 to 4.85 mg kg^{-1} dry mass (Table 3).

Table 3

Effect of increasing nickel concentrations on the heavy metals (mg kg^{-1} dry mass) content in lettuce

Heavy metal	Hydroponic concentration mg Ni dm^{-3}				
	control	0.5	1.0	2.5	3.0
Cd	1.11 ^{a*}	1.70 ^{b}	1.29 ^{ab}	1.31 ^{ab}	1.68 ^{ab}
Cr	4.65 ^{ab}	8.38 ^{b}	4.78 ^{ab}	3.82 ^{a}	2.71 ^{a}
Pb	3.89 ^{a}	3.89 ^{a}	4.51 ^{a}	4.31 ^{a}	4.85 ^{a}

* followed by the same letters do not differ significantly at $\alpha = 0.05$

DISCUSSION

Plant nutrition is essential for plants to germinate, grow, resist diseases and pests. Hence, plants requires a certain percentage of these nutrients to stay healthy. It was observed (Figure 1) that the number of seedlings of the lettuce seeds that emerged decreased with an increasing nickel concentration in the nutrient solutions. There were significant differences in the seedlings germination percentages for all the treatments, with the least value being obtained in the nutrient solution containing the highest dose of nickel (3.0 mg dm^{-3}). Although there were no significant differences in the germination percentages of seeds in the control treatment, 1.0 mg dm^{-3} and 2.5 mg dm^{-3} nickel doses, the highest seed germination percentage was obtained in the nutrient solution containing the least nickel concentration (0.5 mg dm^{-3}). This result corresponds with Khan and Khan (2010), who observed that the number of chickpea seeds germinated reduced with increasing Ni concentrations when exposed to 10, 50, 100, 200, and 400 μg of nickel. This finding is consistent with that of results obtained by Ahmad et al. (2011), who found that nickel is biologically vital in plants but it is hazardous to many plant species when present in high concentrations in soil and nutrient solution. They also discovered that high nickel concentrations in growth media significantly reduce germinability of seeds in a variety of crops. Nickel has a direct effect on the activities of proteases, amylases and ribonucleases, prohibiting digestion of seed and mobilization of food reserves. Excess Ni also has an impact on root nutrition uptake, plant metabolism, photosynthesis, and transpiration, as well as causing ultrastructural changes. Finally, when agricultural crops are exposed to high levels of Ni, all of these processes affected by Ni result in lower yields (Ahmad et al. 2011).

In fresh mass weight of lettuce seedlings (Figure 2), there was a significant difference in the fresh mass weight from all the treatments. Fresh mass of lettuce reduced with the increasing nickel concentrations (0.5, 1.0, 2.5, 3.0 mg dm^{-3}). According to Gajewska et al. (2006), this could be attributable to a drop in plant weight, which could be partially linked to changes in water management and a decrease in the water content in plant tissues. This result affirms the findings of Khan and Khan (2010), who observed a significant reduction in fresh weight of shoot and roots of chickpea when exposed to 10, 50, 100, 200, 400 μg of nickel, but negates the result observed by Sabir et al. (2011) such as that the maize fresh shoot and root mass increased with increased Ni concentrations.

Furthermore, it was observed that increasing the concentration of nickel in the nutrient solution did not result in any significant difference in the chemical composition of lettuce in terms of certain nutrients. For instance, the phosphorus content of lettuce (Table 1) remained 0.9 g kg^{-1} of dry mass for all nickel concentrations (0.5, 1.0, 2.5 and 3.0 mg dm^{-3}) in the nutrient solution of this experiment and although the control had a lettuce phosphorus content of 0.8 g kg^{-1} dry mass, when compared to the other treatments which had 0.9 g P kg^{-1} in dry mass, these values are not statistically significantly. There was no significant difference either in the potassium content of lettuce (Table 1) for all the treatments induced by increasing nickel content in the nutrient solutions, even though the potassium amount in the plants decreased from 68.8 to 54.2 g kg^{-1} of dry mass. Thereby, contradicting the observation that a significant decrease in phosphorus and potassium occurred with an increase in nickel reported in tomato reported by Kumar et al. (2015) and in lettuce leaves by Matraszek and Hawrylak-Nowak (2009).

However, the significant reduction in nitrogen, calcium and magnesium (Table 1) with the increasing nickel concentrations corresponds to the findings of Kumar et al. (2015) and Palacios et al. (1998), who found a significant reduction in macro- (N, K, Ca, and Mg) and micro- (Fe, Mn, and Cu) elements in tomato leaf tissue under severe Ni stress. Similar results were also observed in lettuce leaves by Matraszek and Hawrylak-Nowak (2009). Chen et al. (2009) and Yusuf et al. (2011) explained that once nickel rises above a certain threshold (5-10 mg g^{-1} DW), it might prevent critical macro- and microelements, including K, Ca, Mg, Fe, Cu, Zn, and Mn, from being absorbed, uptaken, and accumulated in plants, resulting in their reduced efficiency. Ni-induced metabolic abnormalities that alter the function of the root could be the reason for a decrease in absorption (Seregin, Kozhevnikova 2006, Kumar et al. 2015). According to Ahmad et al. (2011), the Mg content in sunflower seedlings increased at lower Ni levels (up to 0.35 μM) but declined at higher Ni levels (beyond 0.50 μM) – Matraszek et al. (2017). Matraszek et al. (2017) reported a statistically significant drop in N, P, K, and S concentrations in the nutrient solution deposited in lettuce leaves (0.0004, 0.04, and 0.08 μM), as well as small changes in Ca and Mg accumulation. At the highest Ni level used, a significant reduction in Ca accumulation and relatively prolonged P buildup were seen in shoots (Matraszek et al. 2017). Interfering with other essential metal ions is thought to be the exact source of Ni toxicity in plants. Ni may compete with some nutrients, such as Mg and Ca, in intake and transportation pathways, leading in their exhaustion (Teixeira da Silva et al. 2012, Sreekanth et al. 2013, Charles, Issaa 2014, Matraszek et al. 2017).

The values of the copper content of lettuce from the different treatments vary, ranging from 1.24 to 4.62 mg Cu kg^{-1} (Table 2). It also shows that increasing the concentration of nickel did not have any significant effect on the copper content of the lettuce plants, and the inconsistent progression of the copper content values could be attributed to the fact that nickel is not affected by copper absorption as reported by Yang et al. (1996) in *Lolium perenne* plants. Torres et al. (2016) found a similar phenomenon, noting that the copper content of the maize plant was statistically the same across the nickel treatments, with a modest rise in the copper content as the nickel doses increase.

While it appears that increasing the nickel concentration of the nutrient solution increased the lead content of the plants (3.89 - 4.85 mg Pb kg^{-1}), the data in Table 2 point out that the difference in these values are statistically insignificant. It is evident that increasing or reducing the dose of nickel does not affect the accumulation of nutrients, such as phosphorus, potassium, copper and the toxic metal lead. Negating the opinion, Matraszek et al. (2017) and Turan (2019) found that Ni inhibits the absorption and translocation of micro- and macro-elements in white mustard (Matraszek et al. 2017) and in lettuce (Turan 2019).

However, when the amounts of iron, zinc, manganese, nickel, and cadmium in lettuce plants were compared to different nickel doses, it was shown that raising the nickel concentration had a substantial impact on the elemental content of lettuce. The observed difference is evident in the data shown in the figures above, indicating significantly different and statistically lowest values for the nutrient content of plants growing on the highest doses of nickel. This effect supports previous findings that minor concentrations of Ni are required for plant growth and metabolism, but higher concentrations of Ni cause harmful effects on growth and metabolism by inducing excessive reactive oxygen species production and prohibiting water and essential nutrient uptake and translocation (Matraszek et al. 2017, Rizwan et al. 2019, Jahan et al. 2020). The manganese content was significantly reduced with increased nickel concentration (Table 2). This corresponds with the findings of Torres et al. (2016) in maize, Rahman et al. (2005) in barley shoot, Palacios et al. (1998) in tomato, Khalid and Tinsley (1980) in rye grass. An antagonistic activity between these elements could explain the decrease in foliar manganese caused by increasing nickel doses (Kabata-Pendias 2010).

Zinc contents in lettuce leaves were significantly lowered when nickel was applied. The zinc levels (Table 2) decreased from 211.84 mg kg^{-1} in the control to roughly 174.14 mg kg^{-1} at a nickel concentration of 3.0 mg dm^{-3}. This observation is similar to that of the maize plant in Torres et al. (2016) investigation. Metals like nickel, according to Kabata-Pendias (2010), might be hostile to zinc in tomato plants subjected to nickel dosages. Palacios et al. (1998) found a decrease in the zinc concentration in the root. However, the significant reduction in iron with an increasing concentration of nickel opposes the findings of Torres et al. (2016), where iron increased with an increasing nickel concentration.

An exception to this rule are nutrients like nickel itself and lead which were contained in higher amounts in plants growing in the nutrient solutions containing the highest doses of nickel. The increase in the nickel content with the increasing nickel doses is unsurprising, given the overall nickel uptake by plants is influenced by Ni^{2+} concentrations, plant metabolism, soil or solution acidity, the presence of other metals, and organic matter composition (Chen et al. 2009). An increased nickel content in leaves suggests that this element is highly mobile in plants, whereas its increased content during plant growth indicates that nickel is absorbed in proportion to its concentration (Torres et al. 2016). Mazej and Germ (2009) discovered relatively significant nickel mobility in *Nelumbo Lutea* based on increases in aerial organs of plants.

The nickel content limit according to Commission Regulation (EU) 2024/1987 of 30 July 2024 for leafy vegetables, including lettuce, is 0.5 mg kg^{-1} fresh weight. After taking into account the dry matter content of lettuce, which was on average 5.1%, the recommended maximum nickel limit was converted to Ni content in dry matter and compared with the contents obtained in the tests. The maximum nickel level was not exceeded in lettuce seedlings grown in rockwool in the control combination without nickel addition and at a level of 0.5 mg Ni dm^{-3}. On the other hand, the concentration of 1, 2.5 and 3 mg Ni dm^{-3} of the solution caused the maximum nickel level in lettuce seedlings to be exceeded. The maximum content limit for leafy vegetables in mg kg^{-1} of fresh mass, amounting to 0.10 Cd and 0.30 Pb (Commission Regulation EU 2023/915 of 25 April 2023 for leafy vegetables), was recalculated after taking into account the dry mass content of lettuce. The maximum content limit for Cd and Pb was not exceeded in any of the test combinations.

CONCLUSIONS

The results of this experiment confirm that application of nickel at a minute level (0.5 mg dm^{-3}) improved the biomass of lettuce seedlings and resulted in obtaining the highest amount of N, Ca, Mg, Na, Fe, Cd and Cr in lettuce leaves. It can also asserted that any excess of nickel (3.0 mg dm^{-3}) in the nutrient solution poses a severe effect on seedling emergence and fresh mass of lettuce seedlings, while also retarding the uptake of most macronutrients and micronutrients required in the plant, except nickel itself, which increased when more nickel is added to the solution. The maximum nickel level was not exceeded in lettuce seedlings grown in rockwool at a level of 0.5 mg Ni dm^{-3}. On the other hand, the concentrations of 1, 2.5 and 3 mg Ni dm^{-3} of the solution caused the maximum nickel level in lettuce seedlings to be exceeded. Further research is needed to determine optimal Ni levels for growing plants in hydroponics.

Author contributions

M.B. – conceptualization, A.O., M.B. – formal analysis, M.B. – methodology, A.O., M.B. – investigation, A.O., M.B. – visualization, A.O., M.B. – writing, original draft preparation, A.O., M.B. – writing, review, and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest. They confirm that they have no professional or financial affiliations that could influence the content of the manuscript submitted to the Editorial Board.

REFERENCES

Ahmad, M.S.A., Ashraf, M., Hussain, M. (2011) 'Phytotoxic effects of nickel on yield and concentration of macro-and micro-nutrients in sunflower (*Helianthus annuus* L.) achenes', *Journal of Hazardous Materials*, 185 (2-3),1295-303, available: doi:10.1016/j.jhazmat. 2010. 10. 04 5

Aini, N., Dwi, Yamika W.S., Wahidah Pahlevi, R. (2019) 'The effect of nutrient concentration and inoculation of PGPR and AMF on the yield and fruit quality of hydroponic cherry tomatoes (*Lycopersicum esculentum* Mill. var. cerasiforme)', *Journal of Applied Horticulture*, available: https://doi.org/10.37855/jah.2019.v21i02.20

Aires, Al. (2018) 'Hydroponic production systems: Impact on nutritional status and bioactive compounds of fresh vegetables', Vegetables - Importance of Quality Vegetables to Human Health In*,* available: https://doi.org/10.5772/intechopen.73011

Amjad, M., Hasan, R., Behzad, M., Ghulam, A., Muhammad, I., Muhammad, S., Muhammad, AN., Ali, Z. Muhammad, M.I. (2019) 'Nickel toxicity induced changes in nutrient dynamics and antioxidant profiling in two maize (*Zea mays* L.) hybrids', *Plants* (Basel, Switzerland) 9(1), E5, available: https://doi.org/10.3390/plants9010005

Antonkiewicz, J., Jasiewicz, C., Koncewicz-Baran, M. and Sendor, R. (2016) 'Nickel bioaccumulation by the chosen plant species', *Acta Physiologiae Plantarum,* 38(2), 40, available: https://doi.org/10.1007/s11738-016-2062-5

Brown, P.H., Welch, R.M., Cary, E.E. (1987) 'Nickel: A micronutrient essential for higher plants', *Plant Physiology,* 85, 801-803.

Bosiacki, M., Roszyk, J. (2010) 'The compering methods of mineralization of plant material on the content of heavy metals', *Aparatura Badawcza i Dydaktyczna*, 4, 37-41.

Charles, I.O., Issaa, U.I. (2014) 'Effect of nickel concentrations on *Amaranthus spinosus* uptake of nutrients and heavy metals in soil', *Journal of Applied Phytotechnology in Environmental Sanitation,* 3(3), 87-91.

Chen, C., Huang, D., Liu, J. (2009) 'Functions and toxicity of nickel in plants: Recent advances and future prospects', *Clean – Soil, Air, Water*, 37(4-5), 304-13, available: DOI:10.1002/clen.200800199

Commission Regulation (EU) 2023/915 of 25 April 2023 on maximum levels for certain contaminants in food and repealing Regulation (EC) No 1881/2006. *Official Journal of European Union* 2023.

Commission Regulation (EU) 2024/1987 of 30 July 2024 amending Regulation (EU) 2023/915 as regards maximum levels of nickel in certain foodstuffs. *Official Journal of European Union* 2024.

Domingues, D.S., Takahashi, H.W., Camara, C.A., Nixdorf, S.L. (2012) 'Automated system developed to control pH and concentration of nutrient solution evaluatedin hydroponic lettuce production', *Computers and Electronics in Agriculture*, 84, 53-61, available: https://doi.org/10.1016/j.compag.2012.02.006

Draghici, E.M., Dobrin, E., Jerca, I.O., Ărbulescu, J.M., Jurcoane, S., Luchian, V. (2016) 'Organic fertilizer effect on lettuce (*Lactuca Sativa* L.) cultivated in nutrient film technology', *Romanian Biotechnological Letters* 21(5), 10.

Gajewska, E., Skłodowska, M., Słaba, M., Mazur, J. (2006) 'Effect of nickel on antioxidative enzyme activities, proline and chlorophyll contents in wheat shoots', *Biologia Plantarum,* 50, 653-659.

Gajewska, E., Skłodowska, M (2009) 'Nickel-induced changes in nitrogen metabolism in wheat shoots', *Journal of Plant Physiology,* 166(10), 1034-44, available: DOI: 10.1016/j.jplph.2008.12.004

Hussain, M.B., Shafaqat, A., Aqeel, A., Saadia, H., Muhammad, A.F., Basharat, A., Saima, A.B., Muhammad, B.G. (2013) 'Morphological, physiological and biochemical responses of plants to nickel stress: A review', *African Journal of Agricultural Research*, 8(17), 1596-1602, available: https://doi.org/10.5897/ajar12.407

Jahan, M.S., Guo, S., Baloch, A.R., Sun, J., Shu, S., Wang, Y. (2020) 'Melatonin alleviates nickel phytotoxicity by improving photosynthesis, secondary metabolism and oxidative stress tolerance in tomato seedlings', *Ecotoxicology and Environmental Safety*, 197, 110593, available: doi: 10.1016/j.ecoenv.2020.110593.

Kabata-Pendias, A. (2010) 'Trace Elements in Soils and Plants', ed. CRC Press., available: https://doi.org/10.1201/b10158

Khalid, B.Y., Tinsely, J. (1980) 'Some effect of nickel toxicity on rye grasses', *Plant Soil*, 55, 139-144.

Khan, M., Khan, M. (2010) 'Effect of varying concentration of nickel and cobalt on the plant growth and yield of chickpea', *Australian Journal of Basic and Applied Sciences*, 4(6) 1036-1046.

Kleiber, T., Starzyk, J., Bosiacki M. (2013) 'Effect of nutrient solution, effective microorganisms (EM-A), and assimilation illumination of plants on the induction of the growth of lettuce (*Lactuca sativa* L.) in hydroponic cultivation', *Acta Agrobotanica*, 66(1), 27-38, available: https://doi.org/10.5586/aa.2013.004

Kumar, P., Rouphael, Y., Cardarelli, M., Colla, G. (2015) 'Effect of nickel and grafting combination on yield, fruit quality, antioxidative enzyme activities, lipid peroxidation, and mineral composition of tomato', *Journal of Plant Nutrition and Soil Science*, 178, available: https://doi.org/10.1002/jpln.201400651

Mandizvidza, T.C. (2017) 'Influence of nutrient and light management on postharvest quality of lettuce (*Lactuca sativa* L.) in soilless production systems', Thesis, Stellenbosch University, available: https://scholar.sun.ac.za:443/handle/10019.1/101143

Matraszek, R., Hawrylak-Nowak, B. (2009) 'Macronutrients accumulation in useable parts of lettuce as affected by nickel and selenium concentrations in nutrient solution', *Fresenius Environmental Bulletin*, 18, 1059-1065.

Matraszek, R., Hawrylak-Nowak, B., Chwil, S., Chwil, M. (2017) 'Macronutrient balance of nickel-stressed lettuce plants grown under different sulfur levels', *Communications in Soil Science and Plant Analysis*, 48(6), 665-682, available: https://doi.org/10.1080/00103624.2017.1298779

Mazej, Z., Germ, M. (2009) 'Trace element accumulation and distribution in four aquatic macrophytes', *Chemosphere*, 74, 642-647.

Palacios, G., Gomez, I., Carbonell-Barrachina, A., Pedreno, J.N., Mataix, J. (1998) 'Effect of nickel concentration on tomato plant nutrition and dry matter yield', *Journal of Plant Nutr*ition, 21, 2179- 2191.

Rahman, H., Sabreen, S., Alam, S., Kawai, S. (2005) 'Effects of nickel on growth and composition of metal micronutrients in barley plants grown in nutrient solution', *Journal of Plant Nutrition*, 28(3), 393-404, available: https://doi.org/10.1081/PLN-200049149

Rathor, G., Chopra, N., Adhikari, T. (2014) 'Effect of variation in nickel concentration on growth of maize plant: A comparative over view for pot and hoagland culture', *Research Journal of Chemical Sciences*, 4(10), 30-32.

Rizwan, M., Shafaqat, A., Basharat, A., Muhammad, A., Muhammad, A., Afzal, H., Muhammad, Z.R., Aisha, A.W. (2019) 'Zinc and iron oxide nanoparticles improved the plant growth and reduced the oxidative stress and cadmium concentration in wheat', *Chemosphere*, 214 (January), 269-77, available: https://doi.org/10.1016/j.chemosphere.2018.09.120

Sabir, M., Ghafoor, A., Saifullah, M., Zia-ur-Rehman, M., Ahmad, H., And, T., Aziz, T. (2011) 'Growth and metal ionic composition of Zea mays as affected by nickel supplementation in the nutrient solution', *International Journal of Agriculture and Biology*, 1560-8530, ISSN Online: 1814-959610-297/SBC/2011/13-2-186-190

Seregin, I.V., Kozhevnikova, A. D. (2006) 'Physiological role of nickel and its toxic effects on higher plants', *Russian Journal of Plant Physiology*, 53(2), 257-277, available: https://doi.org/10.1134/s1021443706020178

Shivay, Y.S., Prasad, R. (2019) 'Nickel in environment and plant nutrition: A mini review', *International Journal of Plant and Environment*, 5(04), 239-242, available: https://doi.org/10.18811/ijpen.v5i04.2

Singh, K., Shyam, P. (2011) 'Effect of nickel-stresses on uptake, pigments and antioxidative responses of water lettuce, *Pistia stratiotes* L.', *Journal of Environmental Biology / Academy of Environmental Biology, India* 32 (May), 391-94.

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', *International Journal of Environmental Science and Technology*, 10(5), 1129-1140, available: https://doi.org/10.1007/s13762-013-0245-9

Teixeira da Silva, J., Naeem, M., Idrees, M. (2012) 'Beneficial and toxic effects of nickel in relation to medicinal and aromatic plants', *Medicinal and Aromatic Plant Science and Biotechnology*, 6, 94-104.

Torres, G.N., Camargos, S.L., Weber, O.L.D.S., Maas, K.D.B., Scaramuzza, W.L. M.P. (2016) 'Growth and micronutrient concentration in Maize plants under nickel and lime applications', *Revista Caatinga*, 29, 796-804, available: https://doi.org/10.1590/1983-21252016 v29n403rc

Turan, V. (2019) 'Confident performance of chitosan and pistachio shell biochar on reducing Ni bioavailability in soil and plant plus improved the soil enzymatic activities, antioxidant defense system and nutritional quality of lettuce', *Ecotoxicology and Environmental Safety*, 183 (November), 109594, available: https://doi.org/10.1016/j.ecoenv.2019.109594

Yang, X., Baligar, V., Martens, D.C., Clark, R.B. (1996) 'Plant tolerance to nickel toxicity. II. Nickel effects on influx and transport of mineral nutrient in four plant species', *Journal of Plant Nutrition*, 19(02), 265-279, available:https://doi.org/10.1080/01904169609365121

Yusuf, M., Fariduddin, Q., Hayat, S., Ahmad, A. (2011) 'Nickel: An overview of uptake, essentiality and toxicity in plants. *Bulletin of Environmental Contamination and Toxicology*, 86(1), 1-17, available: https://doi.org/10.1007/s00128-010-0171-1