



Tagetes erecta as a Nickel Phytoremediator: Insights into Accumulation and Growth Response

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Abstract

This study investigates the nickel (Ni) accumulation capacity of *Tagetes erecta* L. in soils with varying Ni concentrations, focusing on its potential for phytoremediation. Preliminary analyses confirmed that approximately 60% of Ni remained bioavailable, facilitating efficient plant uptake. Adsorption-desorption experiments demonstrated that Ni binding to soil was reversible, predominantly driven by weak physical interactions, ensuring the sustained availability of mobile Ni fractions. Morphological assessments indicated that *T. erecta* exhibited optimal growth and increased biomass production at Ni concentrations up to 2000 mg/kg dry matter, with enhanced stem diameter, leaf mass, and flower production. In contrast, plants grown in soils with 6000 mg/kg d.m. Ni showed severe damage and did not survive. Twelve weeks after sowing, flame atomic absorption spectroscopy revealed that flowers were the primary Ni storage sites, followed by stems and leaves. At 2000 mg/kg d.m. Ni, *T. erecta* accumulated over 50 mg/kg d.m. Ni. These findings highlight the phytoremediation potential of *T. erecta*, particularly in moderately Ni-contaminated soils. From the circular economy perspective, phytoremediation offers dual benefits, firstly enabling the recovery of nickel from harvested biomass, which can be reintroduced into supply chains, hence reducing reliance on primary nickel mining and lowering the ecological footprint of metal production, while also contributing to environmental restoration through soil cleaning. Ability of *T. erecta* to accumulate significant Ni levels while maintaining viable biomass production offers a sustainable and promising approach that aligns with circular economy principles.

Keywords Phytoremediation · Climatic chamber · Marigold · Heavy metal pollution · Soil remediation

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Introduction

Nickel (Ni) is one of the most common trace metals discharged into the environment due to its versatile occurrence in the natural environment and various utilizations in technogenic and anthropogenic activities [1]. The 2+ oxidation state (Ni^{2+}) is the most common also in environmental and biological systems, combined with several other elements, that can be present in soil [2]. Ni as an environmental pollutant enters into nature through several human sources such as from the roadsides caused by the metal part corrosion of vehicles [3], moreover, railway transportation is also poses a risk of pollution in soils [4]. Ni is released from coal combustion, metal production [5], and industrial electroplating processes [6]. The erosion of rocks and volcanic eruptions are the most typical natural sources of this element [7]. It may enter the food chain and pose ecological and human health risks [8], including contact dermatitis; headaches; gastrointestinal and/or respiratory manifestations; lung fibrosis; cardiovascular diseases; lung cancer; nasal cancer; and epigenetic impacts [2] furthermore, it can induce hepatotoxicity [9].

As a result of the harmful effects of nickel on nature and human life, nickel concentration has been limited by some policies. According to the European Food Safety Authority (EFSA), the tolerable daily intake (TDI) was established in $13 \mu\text{g Ni/kg}$ body weight [10]. In drinking water, $70 \mu\text{g Ni/L}$ [11] is the maximum level stated by the World Health Organisation (WHO). The level is maximized for the soil and geological medium in 40 mg Ni/kg d.m. [12, 13].

Several remediation technologies for nickel-polluted soil have been investigated in the last few years such as soil washing [14]. Electrokinetic [15], and microbial [16] remediation is also one of the most promising techniques. Due to the recognition of Ni as a crucial microelement for more complex, further evolved plants, especially in low concentrations such as $0.5\text{--}10 \text{ mg/kg d.m.}$ [17], phytoremediation is an encouraging Ni removing process. Ni supports the urease enzyme activity which is responsible for the assimilation of urea [18] moreover, it is a pillar of photosynthetic electron transport and chlorophyll biosynthesis [2].

Tagetes erecta (*T. erecta*) is a widely available ornamental plant. It is easily accessible, cost-effective, and requires no special treatment, hence, it can be found in cities for aesthetic purposes. As long as its reproduction rate is high, the life cycle is quite short *T. erecta* is a good candidate to investigate phytoremediation in case of different circumstances [19]. Furthermore, *T. erecta* is more efficient in heavy metal accumulation (especially in nickel) than other *Tagetes* species in various heavy metal-contaminated soils [20]. Khilji et al. treated the plants by inoculating bacteria, resulting in biomass increase and higher chromium, cadmium, and lead uptake [18]. Sharma and Mathur investigated the Zn accumulation capacity of *T. erecta* and *Helianthus annuus*, where *Helianthus annuus* is proven to be more productive [21]. Coelho et al. proved that *T. erecta* is a Cr hyperaccumulator species [22]. The seed germination and the heavy metal tolerance in the hydroponic medium of *T. erecta* were investigated by Bhurat et al. In 200 and 250 mmol Ni^{2+} containing media 60–70% of seeds were germinated while in the case of 300 mmol metal concentration, 20% of seeds were able to germinate. In hydroponic medium, plantlets survived up to 250 mmol concentration of Ni^{2+} with a reduction in the overall growth [23]. Puhalsky et al. examined the heavy metal accumulation beside humic acid support. The experiments were carried out in the vegetation phase in different soil samples. Ni accumulation is higher in roots than in stems, as stated in this research [24].

Following phytoremediation, plant biomass accumulates toxic levels of heavy metals, posing a risk of secondary pollution if managed improperly. Within the framework of the circular bioeconomy, this biomass is no longer considered waste but a valuable resource. Rather than disposal, it can be transformed into commercially viable products such as bio-char, biogas, bioethanol, biodiesel, and metal nanoparticles. This valorization not only mitigates environmental risks but also generates economic returns, advancing both ecological and industrial objectives [25]. Hyperaccumulator plants, which extract heavy metals from contaminated substrates, produce biomass that is reintegrated into the production cycle. Such a system minimizes the need for external inputs and significantly reduces waste generation [26]. Finally, the circular bioeconomy model supports global climate goals. By replacing traditional remediation technologies, which are often energy-intensive and carbon-intensive, with low-emission, bio-based alternatives, it contributes to climate change mitigation [27].

In this study, the Ni accumulation capacity of *T. erecta* L. and the viability of plants in different concentrations of Ni-contaminated soils were studied in a climate chamber until the flowering stage (12 weeks). The goal is to determine which plant organ stores most of the accumulated nickel. First, the homogeneity and adsorption-desorption properties of the experimental soils were analyzed. Then, the morphological and structural characteristics of plants were observed over the growing phase. Finally, the accumulated Ni quantity was detected in the case of all aboveground plant organs. The ambition of this work is to take a step towards a circular economy through plants, both in terms of waste recovery and remediation, through a phytomining process, utilizing the accumulation capacity of the plants to both clean the soil and extract metal, which can be further used as raw material.

Materials and Methods

Preparation of Experimental Pots

In this study, the effect of nickel pollution at different concentrations on the growth of *T. erecta* L. was examined from the plating phase to the flowering stage. The seeds of *T. erecta* L. were obtained from commercial gardening suppliers (Rédei Kertimag Ltd, Réde, Hungary). For the planting medium, commercially available general soil (Garri universal potting soil, OBI GmbH & Co KG, Veszprém, Hungary) with the following properties was used seen in Table 1.

The soil mixing process was carried out one day before the planting. The soil was contaminated with $\text{NiCl}_2 \cdot 6 \text{H}_2\text{O}$ (Merck, ACS) in five concentrations (0, 200, 1000, 2000, and 6000 mg/kg d.m. Ni). The soil mixing process ensured homogeneity, which was confirmed by Flame Atomic Absorption Spectrometry (FAAS) (Thermo Scientific iCE 3000 series,

Table 1 The properties of the planting soil

Component	Content (w/w% d.m)
N	> 0.3
P ₂ O ₅	> 0.1
K ₂ O	> 0.1
Organic matter	> 40%
pH	7.0 +/-0.5

Waltham, USA) measurements [28, 29]. The following steps were taken during the mixing process.

- Step 1: Prepare the right amount of $\text{NiCl}_2 \cdot 6 \text{H}_2\text{O}$ to reach the desired concentrations in terms of dry matter (0–6000 mg/kg d.m.), and dissolve it in 500 mL water.
- Step 2: Feeding the soil (14 kg) into a conventional rotary concrete mixer. (OBI GmbH & Co KG, Veszprém, Hungary)
- Step 3: Pouring NiCl_2 solution (500 mL) into the concrete mixer.
- Step 4: Use a paddle mixer (OBI GmbH & Co KG, Veszprém, Hungary) and repeat the mixing process as the soil dries.

The paddle mixer was utilized to disperse the formed granules, and after the soil dried, a crumbly planting medium was formed by repeating the process.

The seeds were initially sown in uncontaminated general potting soil to ensure successful germination. This soil was used for the growing of “control” plants. Two seeds were planted per pot. After 4 weeks, the plants were transplanted into the Ni-contaminated soil. Three replicates per treatment were implemented. Thus, the average value of the amount of nickel accumulated in *T. erecta* L. is calculated from the three data sets for each collected plant part (flower, stem, leaves, roots). Throughout both the germination and raising phases, plants were cultivated in a climatic chamber (POL-EKO Climatic Chamber KK 1200, Wodzisław Śląski, Poland) under the conditions shown in Table 2.

The pots were watered twice a week, 100 ml/occasion, if required, the quantity was adjusted based on our previous experience with the climatic chamber. The condition and development of the plants were visually monitored during the experiment. After the 12-week growing period, the plant height, the number of stem branches, the diameter of the stem, and the quantity of reproductive organs were recorded.

Determination of Ni Content in Soil and Plant Samples

The key goal of the investigation was to determine the nickel accumulation capacity of the *T. erecta* L. To detect the nickel content in both initial soil samples and plant tissues, FAAS measurements were performed.

Sample Preparation for FAAS Analysis

Microwave Digestion The soil samples were dried in an oven at 105 °C to constant weight. Plant samples (flowers, leaves, stems, and roots) from 12-week-old plants were separated, cut, and dried at 105 °C, then gently grounded. Then plant samples were incinerated at 550 °C for 4 h, to produce the ash for Ni determination. Samples were then cooled down to room temperature. The samples were digested using an Anton Paar Multiwave 3000 device

Table 2 Cultivating conditions in the climatic chamber

Parameters	Values
Daylight cycle length	16 h
Daytime temperature	22 °C
Night cycle length	8 h
Night time temperature	20 °C
Relative humidity	70%

(Anton Paar GmbH, Graz, Austria) with microwave energy of 600 W, in 6 mL of aqua regia (4.5 mL HCl + 1.5 mL HNO₃, VWR Chemicals, analytical grade). The sealed vessels (HF100) were heated to 175 °C for 30 min, followed by a 30-minute contact time. After cooling, the samples were diluted to 25 mL and analyzed using FAAS.

Lakanen-Ervio Digestion To quantify the maximum plant-available nickel ion concentration in the experimental soil under the given conditions, Lakanen-Ervio digestion was conducted according to the MSZ 21470-50 standard. The plant-available nickel concentration was measured using a mixture of EDTA (VWR Chemicals, > 95%), acetic acid (VWR Chemicals, 99–100%), and ammonia 25% (VWR Chemicals, > 95%).

Adsorption-Desorption Batch Test Adsorption-desorption tests assessed Ni mobility, as effective phytoremediation requires Ni to be in soluble, mobile forms [30]. Soil samples (15 g) were mixed with Ni solutions (0–1000 mg/L) in 150 mL volumes, agitated at 200 rpm on an orbital shaker (DLab, SK-O330-Pro type, Malaysia) for 24 h at 20 °C, then filtered through 0.45 µm filters. Desorption was analyzed by shaking 10 g of Ni-treated soil with 100 mL of distilled water for 24 h under the same conditions. The samples were then filtered, and the Ni concentration in the supernatant was determined using FAAS.

The presence or absence of adsorption-desorption hysteresis was evaluated by comparing the adsorption isotherms with the corresponding desorption curves. The adsorption and desorption data were compared with the Freundlich isotherm (Eq. 1), which is suitable for a wide range of concentrations and non-linear adsorption processes [31, 32].

$$q_e = K_F \cdot c_e^n \quad (1)$$

Where q_e is the adsorbed species concentration [mg/g], c_e is the sorbate concentration in solution [mg/L], and K_f [L/mg] and n are empirically determined constants.

The hysteresis index (H) [33, 34] was calculated (Eq. 2) to evaluate sorption reversibility:

$$H = \frac{1/n_a}{1/n_d} \quad (2)$$

Where n_a and n_d constants are derived from the Freundlich adsorption and desorption isotherms, respectively.

Analytical Analysis

FAAS measurements were performed using a Thermo Scientific iCE 3600 FAAS. Calibration standards (1.0, 5.0, and 10.0 mg/L) were prepared from a 1000 mg/L Supelco Ni standard. The instrument settings were as follows: Ni wavelength = 232.0 nm, bandpass = 0.1 nm, background correction = D₂, lamp current = 75%, air-acetylene gas purity = 4.6 (Messer Hungarogáz Ltd.).

Results and Discussion

Preliminary Experiment

Determination of Nickel in Polluted Model Soil

Before the phytoremediation, preliminary experiments were conducted to validate the soil preparation method. First, the bioavailable Ni concentration was studied over a broad range of Ni-concentration. The results show (Fig. 1) that most of the Ni ($\sim 60\%$) is in Ni^{2+} plant-available form, even at the highest concentration (52.18% at 20500 mg Ni/kg d.m.). This confirms that the present nickel pollution is available for plants, enabling an accurate assessment of *T. erecta*'s accumulation capacity.

Determination of Plant Tolerable Concentration of Metal Ion

To determine the maximum tolerable Ni concentration in soils for *T. erecta* L. the selection of the Ni concentration range was based on literature, real contaminated areas [35, 36], and accumulation capacity of the plant [37, 38].

Ensuring the homogeneity of Ni-contaminated soils is an essential step to provide the representability of the experiments. The results demonstrate (Fig. 2) that the standard deviation among the replicates slightly increases with the Ni concentration (16.40, 130.61, 184.03, 211.72 mg Ni/kg d.m.). However, with a maximum standard deviation of less than 3.5%, the soil preparation method meets accuracy requirements, confirming the homogeneity of the experimental soils.

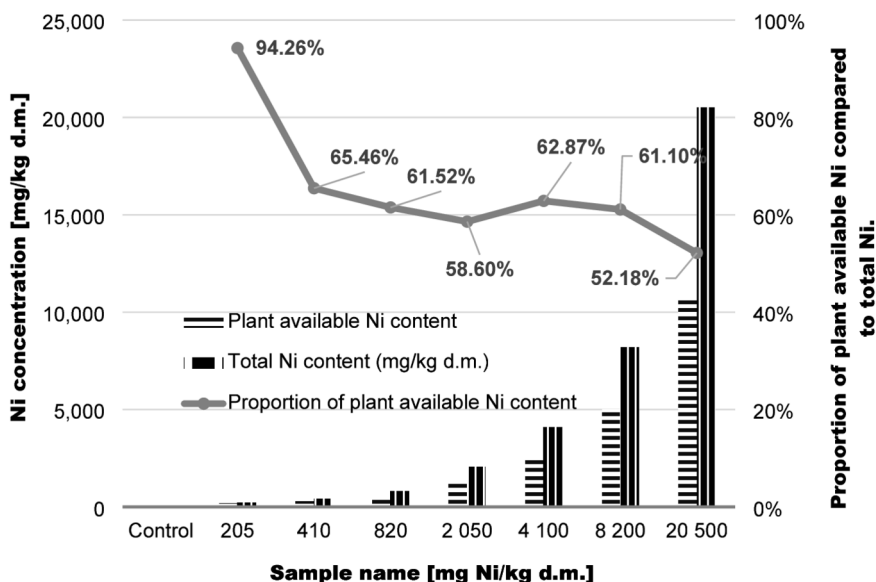


Fig. 1 Plant available nickel content and its share of the total

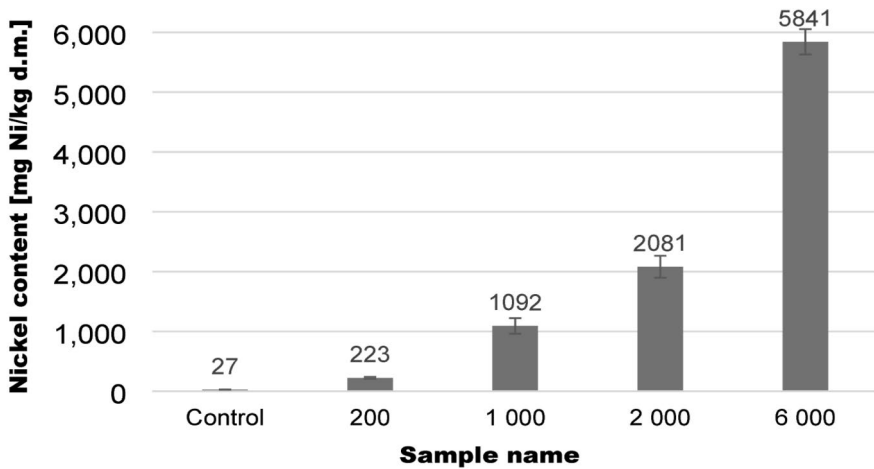


Fig. 2 Homogeneity test results of soils treated with different nickel concentrations (sample name indicates Ni content in mg/kg dry matter)

Nickel Ion Sorption Soil Capacity

Experimental results indicate that Ni applied at varying concentrations was significantly adsorbed onto soil particles (Fig. 3); However, adsorption-desorption studies indicated that this binding was largely reversible. The absence of adsorption hysteresis confirms that the adsorbed nickel did not form stable, irreversible bonds with the soil surface [33, 39].

Since $H < 1$ ($H = 0,9411$) (Table 3), this confirms that there is no or negligible sorption hysteresis, meaning adsorption and desorption intensities are effectively equivalent [34]. This suggests that the sorption-desorption process is fully reversible, governed primarily by weak physical interactions.

Where R^2 is the coefficient of determination, k , and n are empirically determined Freundlich constants, SSR is the residual sum of squares and H-index is the hysteresis index.

Thus, the reversibility is advantageous as it allows for the continuous availability of mobile nickel fractions, facilitating contaminant removal via phytoremediation. Furthermore, since a significant portion of the adsorbed nickel does not remain stably bound in the soil, remediation efficiency is enhanced, and long-term pollution can be minimized.

Morphological and Structural Characteristics of Plants

The visual assessment of the plants indicates that the transplantation process from the general potting soil to the Ni-contaminated soil was carried out gently, as no significant morphological differences were observed in the initial stages of growth. Furthermore, significant morphological and structural variance could not be noticed among the plants planted in different Ni-concentration soils during the early phases of development. However, around six weeks of age, plants cultivated in soil with the highest nickel concentration (6000 mg Ni/kg d.m.) exhibited red discoloration on both leaves and stems.

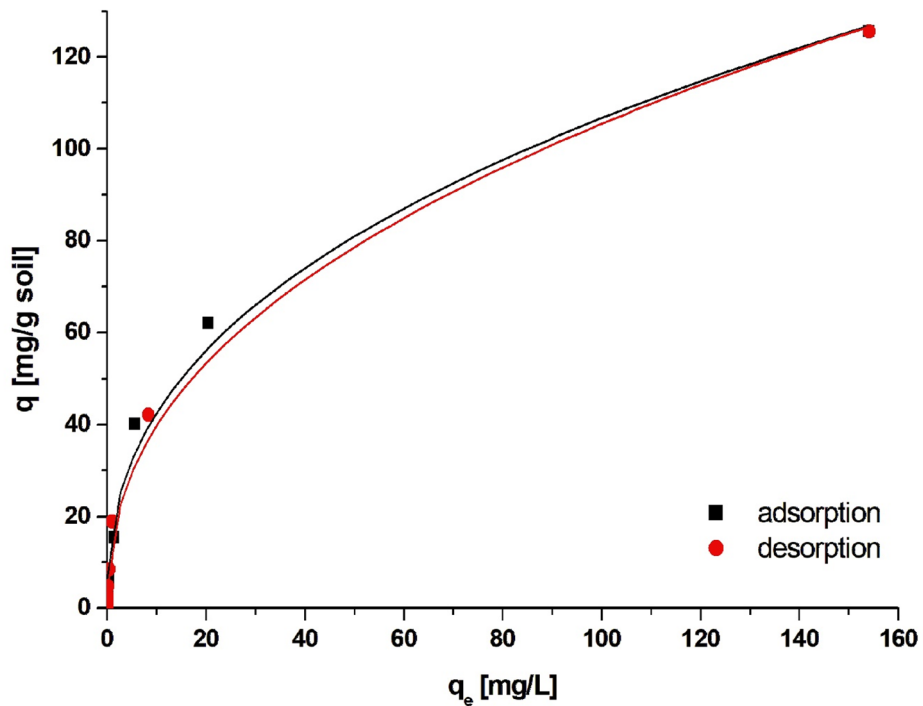


Fig. 3 Results of adsorption and desorption tests

Table 3 Evaluation of Freundlich isotherm and the result of H-index

	R^2	k	n	SSR	H-index
Adsorption	0.9907	16.97	0.3992	179.10	0.9411
Desorption	0.9912	14.97	0.4239	110.89	

All three replicates in this group began to desiccate, with irreversible deterioration occurring within a few days (Fig. 4). Subsequently, plants at the highest concentration dried out by the end of the experiment (Fig. 5).

This research focused on the Ni accumulation in the aboveground biomass, as accessible harvesting is a key factor for potential scale-up applications. After 12 weeks, the experiment was completed. The soil was carefully swept away from the stems, and the stems were excised above the root zone in all samples (Fig. 5). Plant height and biomass were measured, and plants were further characterized based on stem diameter, flower size, flower count, and number of branches.

The end of the life cycle of the plants was defined as the flowering stage of the control group. According to John et al. [40] and Wei et al. [41], this stage is optimal for the uptake of heavy metals by their investigated plants. Similarly, S.K. Singh [42] reported enhanced Ni uptake during the flowering stage in *Tagetes patula*. The flowering phase was reached within 12 weeks, and as shown in Fig. 5, aside from the dried-out samples (6000 mg Ni/kg d.m. sample), flowers were also observed in the other concentrations. All plants reached the

6 weeks



Fig. 4 Plant development at week 6, morphological changes in plants grown in soil with 6000 mg Ni/kg d.m

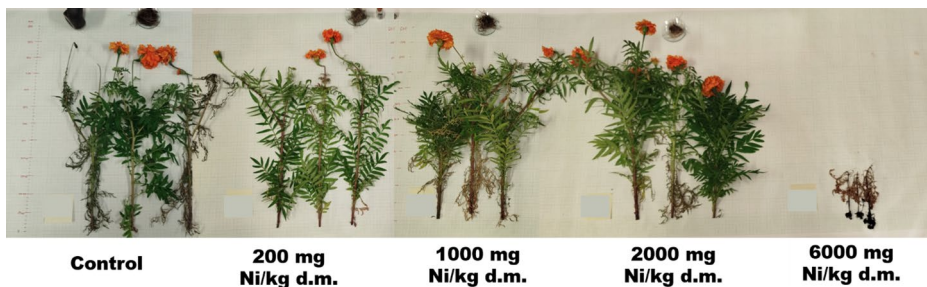


Fig. 5 12 weeks old plants used for determination of Ni accumulation

required growth height of 40–60 cm, with no significant morphological anomalies, although there were slight differences in stem diameter, flower size, and number of flowers.

It can be observed that the presence of nickel caused the death of plants only at the highest concentration of 6000 mg Ni/kg d.m. No negative effects were observed at concentrations of 1000–2000 mg Ni/kg d.m. in all three replicates, these test plants grew slightly bigger than the control group, which is visibly observable (e.g. more lush and fuller leaves, more branches, bigger flowers). In terms of aboveground biomass, the presence of nickel seems to have had a positive effect on plant development to a certain extent.

Analysis of stem properties (Fig. 6a) revealed that plants grown in soil with 200 mg Ni/kg d.m. developed the most fragile stems compared to those in higher Ni-concentration

soils, including the control group. The average number of stem branches was approximately twice as high in the control and highest Ni-contaminated soils (3.0, 3.7, and 3.3 branches) compared to those in the 200 mg Ni/kg d.m. group (1.3 branches). Additionally, the average stem diameter was 1.5 times larger in the other Ni concentrations (7.5 mm, 8.1 mm, and 7.6 mm) compared to 200 mg Ni/kg d.m. (5.6 mm). Similar trends were observed for flower development (Fig. 6b), with the lowest average flower and bud count (~ 1.5) recorded at 200 mg Ni/kg d.m. Flower and bud numbers increased at 1000–2000 mg Ni/kg d.m., with the highest flower yield (~ 3.3) observed at 2000 mg Ni/kg d.m. Notably, flower diameter decreased progressively with increasing Ni concentration (57.3 mm, 45.0 mm, and 36.7 mm), except for a significant increase at 2000 mg Ni/kg d.m. (65.7 mm).

Plants at concentrations of 200 mg/kg d.m. are unlikely to have developed full tolerance to nickel stress, whereas those at higher concentrations (e.g. 1000–2000 mg/kg d.m.) demonstrated greater adaptability. At higher concentrations, plants may activate mechanisms such as nickel sequestration or the upregulation of antioxidant enzyme activity to mitigate toxicity, thereby preventing severe damage [43, 44]. In contrast, at 200 mg/kg d.m. nickel concentrations may be insufficient to trigger these protective responses, leading to more pronounced toxic effects.

Examining the biomass yield at the end of 12 weeks (Fig. 6c) indicated that the control plants produced more biomass than the dose in the 200 mg Ni/kg d.m. group across all the tested plant organs. Biomass yield is twice as high in the case of 1000, 2000 mg Ni/kg d.m. compared to the 200 mg Ni/kg d.m., suggesting that nickel may enhance leaf and stem biomass accumulation, as also evident from photographic documentation.

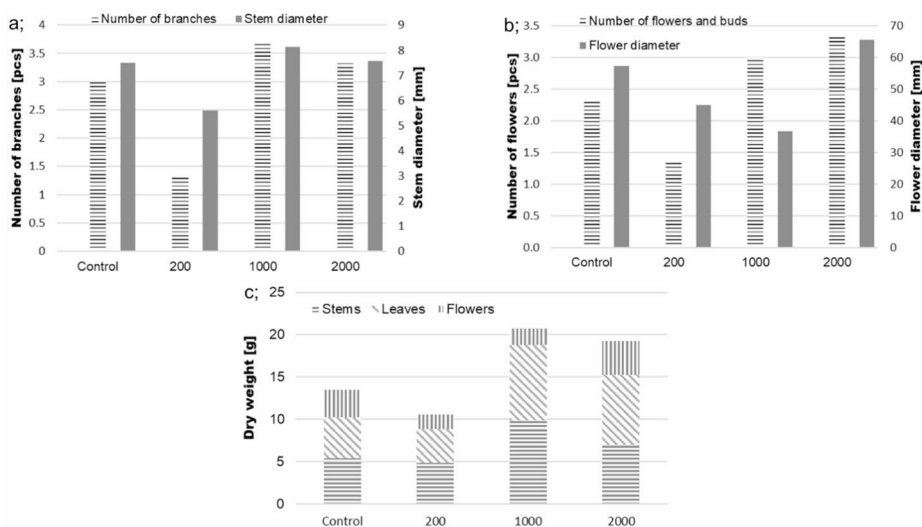


Fig. 6 **a** Number of branches and stem diameter, **b** Number of flowers, buds, and flower diameter, **c** Proportion of different plant organs in dry matter Sample naming: Soil concentration [mg/kg d.m.]

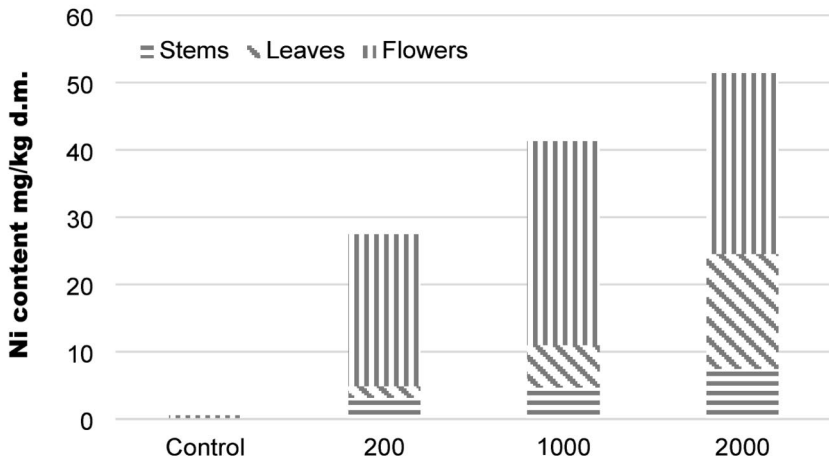


Fig. 7 Nickel concentration in different plant organs in the aboveground biomass (Sample naming: Numbers: Soil concentration [mg/kg d.m.]

Nickel Content Determination in Aboveground Plant Biomass

Phytoextraction or phytoaccumulation refers to the uptake and translocation of pollutants into harvestable aboveground plant parts. This study focused exclusively on the aboveground biomass, including stems, leaves, and flowers, as phytoextraction enables metal removal through simple harvesting [45, 46]. The nickel content of the plants was analyzed in all aboveground plant organs using atomic absorption spectroscopy following sample preparation. The results (Fig. 7) clearly demonstrate that the *Tagetes erecta* test plant effectively accumulates nickel, with the highest concentration detected in the flowers (and/or seeds) (62.62%, 82.01%, 73.37%, 52.16%). The remaining accumulated Ni was approximately evenly distributed between the stems and leaves. The total Ni accumulation increased proportionally with soil Ni concentration. At the highest assessable concentration (2000 mg Ni/kg d.m.), total Ni accumulation exceeded 50 mg Ni/kg d.m. which is lower than the levels reported by Derya et al. for shoots at a soil concentration of 50 mg/kg. However, our research demonstrates that even at significantly higher concentrations, the plant survives and is capable of accumulating nickel, however in smaller amounts in the aerial parts [37]. Ain et al. investigated *Tagetes erecta* in industrially contaminated soil, where the Ni uptake was measured at 8.77 mg/kg in leaves and 6.05 mg/kg in stems, less than half of the values observed in this study. However, their research did not examine Ni accumulation in flowers [47]. Seregin et al. investigated the Ni hyperaccumulation potential of *Noccaea japonica* and *Noccaea caerulea*, measuring the Ni uptake in plants ranging from 10 to 80 mg/kg d.m. in different soil types. Their finding indicated significant variability in Ni accumulation between roots and shoots, depending on pollution levels [48]. Sheoran et al. categorized hyperaccumulators into two groups, distinguishing between natural hyperaccumulation and induced hyperaccumulation. Induced hyperaccumulation refers

to cases where metal uptake can be enhanced in hyperaccumulator species or stimulated in naturally non-hyperaccumulator species with high biomass yields (e.g. *Zea mays*, *Helianthus annuus*) through chemical intervention. This distinction expands the range of suitable plant species for large-scale field applications [49]. In addition to chemical modifications, Ying et al. found that bacterial inoculation seemed to effectively protect plants from Ni-induced growth inhibition while enhancing Ni uptake in *Brassica juncea* and *Brassica oxyrrhina* grown in soil contaminated with 450 mg/kg Ni [50]. Similarly, Khilji et al. studied microbe-assisted phytoremediation with *Tagetes erecta* and observed beneficial effects such as enhanced antioxidant activity, increased biomass production, and improved plant defense mechanisms [18]. Serigne et al. investigated the nickel accumulation potential of *Bornmuellera emarginata* under varying Ni concentrations and pH levels in hydroponic conditions. Their findings indicated that at a 10 μM Ni solution, the plant accumulated more than 5000 mg/kg d.m. Ni, which is an exceptionally high value. However, *B. emarginata* is not native to Hungary and thrives in warmer climates, presenting challenges for its application in open-field experiments [51]. Tognacchini et al. proposed phytoremediation as a viable method for nickel retention from galvanic sludges with low nickel concentration [1]. Additionally, Kriti et al. demonstrated that bacterial augmentation could enhance Ni-Cd availability in Ni-Cd battery electrolyte-contaminated soils. These studies collectively highlight the potential for scaling up phytoremediation applications in existing contaminated sites [52].

This research highlights that *T. erecta* not only tolerates moderate nickel pollution (1000–2000 mg/kg d.m.) but also exhibits optimized biomass growth under these conditions. This finding represents a significant contribution to phytoremediation research, as few plant species demonstrate both metal tolerance and enhanced growth in the presence of heavy metals. The study employed a unique methodological approach to ensure soil homogeneity, thereby minimizing experimental uncertainties. This methodology may serve as a valuable reference for future phytoremediation studies involving other heavy metal-contaminated soils.

The phytoremediation potential of *T. erecta* may be particularly relevant in industrial or mining areas with moderate nickel pollution. In such areas, phytoremediation not only facilitates contaminant removal but also enables resource recovery through phytomining, contributing to the development of a circular economy. Conventional soil remediation techniques (e.g. soil washing) often require chemical additives that can cause long-term environmental impacts. In contrast, *T. erecta* provides a natural, sustainable alternative, reducing soil pollution while minimizing secondary environmental damage. Furthermore, phytoremediation, particularly through the use of *T. erecta*, presents substantial social benefits by providing a low-cost and environmentally friendly solution for soil pollution. This approach is particularly advantageous in developing countries where access to advanced soil treatment technologies is limited.

Conclusion

The results of this study confirm the significant potential of *Tagetes erecta* L. for the phytoremediation of nickel-contaminated soils. The plants demonstrated efficient Ni uptake across a range of concentrations, with the bioavailability of Ni being sufficiently high to

support effective plant absorption. Adsorption-desorption experiments confirmed that Ni binding was reversible, primarily governed by weak physical interactions, ensuring the continuous availability of mobile Ni²⁺ fractions for the plant.

Morphological observations indicated that *T. erecta* exhibited optimal growth and increased biomass production in soils with Ni concentrations up to 2000 mg/kg d.m., as evidenced by enhanced stem diameter, leaf mass, and flower production. However, plants grown in soils with 6000 mg/kg d.m. Ni experienced severe damage and failed to survive, suggesting that while *T. erecta* can tolerate moderate levels of pollution, higher concentrations lead to significant stress responses that hinder growth and survival.

Nickel accumulation revealed that flowers take up Ni in higher concentrations, this makes it advantageous to postpone the harvesting phase until after flowering.

These findings emphasize the promising potential of *T. erecta* for phytoremediation in moderately Ni-contaminated soils. Its ability to accumulate a substantial amount of Ni while maintaining viable biomass production positions it as an effective and sustainable solution for reducing soil Ni pollution. Besides that, this research underscores the role of phytoremediation in promoting circular economy objectives by transforming environmental pollutants into recoverable resources. By harvesting metal-enriched biomass, it becomes feasible to close material loops, reduce dependence on primary mining, and promote sustainable soil use. Future research should focus on investigating the long-term stability of Ni accumulation in *T. erecta* and its applicability in large-scale soil remediation efforts, as well as its potential for long-term soil recovery and sustainability. Furthermore, conducting complementary studies could also be helpful in understanding the interactions of the test plant with other heavy metals or pollutants, such as cadmium and lead.

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Declarations

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

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