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Impact of Foliar Conditioner on Translocation and Bioaccumulation of Trace Elements in Paulownia (*Paulownia Siebold & Zuccarini*, 1835)

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Abstract: The main objective of this engineering study was to investigate the impact of foliar conditioners on the translocation and bioaccumulation of trace elements in Paulownia trees. Paulownia, commonly known as the "empress tree," serves as a promising research subject within the environmental engineering context. The study focused on analyzing the effects of foliar conditioners on trace elements in this species, taking into account ecological and economic aspects. The obtained results aim to contribute to the development of effective strategies supporting the healthy growth of plants, addressing environmental protection concerns, and offering practical applications in Paulownia plantation management.

Keywords: foliar conditioner, translocation, bioaccumulation, paulownia, trace elements

INTRODUCTION

The dynamics of forest ecosystems constitute a significant area of research, especially in the context of introducing new technologies, such as conditioners, which have the potential to impact the translocation and bioaccumulation of trace elements in plants. Paulownia (*Paulownia Siebold & Zuccarini*, 1835), commonly known as the "empress tree" due to its impressive growth characteristics, serves as a promising research subject in environmental engineering. In the face of changing climate and increasing pressure on sustainable management of natural resources, the search for effective tools to improve plant and ecosystem conditions becomes particularly important. Conditioners, substances introduced into the soil or applied to plant leaves, have the potential to stimulate growth, enhance resilience, and optimize metabolic processes. However, there is limited research on the influence of these substances on the transport and accumulation of trace elements in plants, especially for tree species like Paulownia.

The aim of this study is to investigate the impact of conditioners on the translocation and bioaccumulation of trace elements in Paulownia. This analysis is significant from both an environmental protection perspective and practical application, particularly in the context of cultivating and managing Paulownia plantations. Valuable insights into the response of this tree to conditioners can contribute to the development of effective strategies supporting healthy plant development and minimizing potential threats to forest ecosystems. However, before it is applied in practice, further research on the mechanisms of this ability and the impact of hyperaccumulation on the plant itself is necessary. In the context of sustainable management of natural resources, Paulownia can not only provide high-quality wood but also play a significant role in the reclamation of contaminated areas. Its potential as a hyperaccumulator opens new perspectives for plants in terms of environmental protection and sustainable development.

Soil conditioners are chemical substances aimed at improving the physicochemical properties of the soil and supporting the metabolic processes of plants. In the context of restraining the translocation and bioaccumulation of trace elements in the aboveground parts of plants, soil conditioners can play a significant role.

1. Chelation of trace elements: Soil conditioners often contain chelating substances that can form complexes with trace elements in the soil. These complexes hinder or limit the plant's access to these trace elements, reducing their absorption and transport to the aboveground parts.
2. Stimulation of soil microorganisms: Improving soil condition with soil conditioners may promote the activity of soil microorganisms. These microorganisms can affect the availability of trace elements by accelerating their chemical transformations or binding them in a form less accessible to plants.
3. Improvement of soil structure: Soil conditioners often contain substances that improve soil structure, such as organic matter. Improving soil structure can influence its water retention, which in turn may affect the mobility and availability of trace elements to plants.
4. Reduction of oxidative stress: Some soil conditioners have antioxidant properties that help plants cope with oxidative stress. This stress can affect the plant's ability to concentrate trace elements, and soil conditioners can aid in maintaining metabolic balance.
5. Soil pH regulation: The content of soil conditioners can influence soil pH. Optimal pH can affect the availability of various elements to plants by regulating their chemical form.

Analyzing the effects of soil conditioners on trace elements in Paulownia cultivation can also broaden our understanding of the mechanisms of transport and accumulation of these substances in plants. This is important not only for the field of environmental engineering but also for ecology and plant biology. This work represents a step towards a better understanding of the impact of modern technologies on the functioning of forest ecosystems, with an emphasis on plants of potential economic and ecological importance.

MATERIALS AND METHODS

Test plant was a hybrid of Paulownia sp. Tomentosa x Fortuneii x Kawamii (Z-07NT). Soil conditioner based on waste leonardite from PAK Adamów, produced by INCO sp.z o.o., was used in doses of 1 and 5 t/ha (hereafter referred to as Fc1 and Fc5); it contained 100 kg N, 35 kg P, and 125 kg K. For fertilization of Fc1 and Fc5, 60 kg N was used in the form of urea (46% N). Planting of the test plant was carried out on September 10, 2018.

Prior to the experiment, soil excavation to a depth of 150 cm was conducted each year. The profile was morphologically described. In soil samples from different levels, the following were determined:

• pH in a KCl solution with a concentration of 1 mol.dm-3 using the potentiometric method, with the H/1131 combination electrode and pH 301 meter from Hanna Instruments, with a soil-to-solution weight-to-volume ratio of 1:2.5,

• total content of phosphorus, potassium, cadmium, lead, chromium, nickel, zinc, and copper in the soil after mineralization in a mixture of concentrated HCL and HNO_3 in a ratio of 3:1, using the ICP-AES method on an inductively coupled plasma emission spectrometer from Perkin Elmer model Optima 3200 RL.

In the collected plant material of Paulownia (aboveground and roots), the following were determined:

• fresh weight yield of the test plant,

• dry matter content using the drying-weighting method (at 105°C) [Kalembasa et al., 1989],

• calculated dry matter yield of Paulownia (*Paulownia Siebold & Zuccarini*, 1835),

• content of P, K, Cd, Pb, Cr, Ni, Zn, and Cu after dry mineralization using the ICP-AES method,

• calculated bioaccumulation and translocation coefficients of selected heavy metals and trace elements.

RESULTS

The field experiment was conducted in 2019, 2020, and 2021 on three soils classified as loamy soils (P order), loamy soils (PP type), and loamy soil with gley (PPgg subtype) [Systematyk Gleb Polski, 2019]. In subsequent years, the experiment was conducted in the fields of the Specialized Farm in Malechówko (Sławno poviat, Zachodniopomorskie voivodship) on soils with a sandy clay granulometric composition. The soil pH in different levels was acidic. The total carbon and nitrogen content in the analyzed samples of humus levels were characteristic for these types of soils and decreased within the soil profile.

Table1. Selected properties of the examined soils before the experiment setup.

Genetic level	**pH_{KCl}**	**$C_{całk.}$** ($g \cdot kg^{-1}$)	**$N_{całk.}$** ($g \cdot kg^{-1}$)
2019 Podzolic gley soils (PPgg)			
A_p	4,40	10,8	1,1
E_t	5,58	9,4	0,6
$B_{t(gg)}$	5,41	4,6	0,2
C_{gg}	4,37	1,3	-
2020 Podzolic gley soils (PPgg)			
A_p	4,75	9,1	0,7
E_t	5,20	1,0	0,1
$B_{t(gg)}$	5,47	0,6	-
C_{gg}	4,85	0,2	-
2021 Podzolic gley soils (PPgg)			
A_p	5,17	12,6	1,0
E_t	5,39	10,4	0,8
$B_{t(gg)}$	5,40	3,8	0,3
C_{gg}	4,91	1,7	0,1

Analyzing the total cadmium content in the soil in the years 2019-2021, under the conditions of the conducted experiment (Table 2), significant differences were observed in its content depending on the applied fertilization, as well as for the interaction between fertilization and varieties, and fertilization and years of study. The significantly highest content of this element was found in the soil fertilized with Fc1+N. The smallest amounts of cadmium in the soil were recorded for the unfertilized object. The difference between the highest and lowest levels of total cadmium content in the soil for the applied fertilization was 60%, indicating that the overall level of cadmium in the soil was relatively low, especially considering that, according to current regulations, the maximum cadmium content in soil used in Poland cannot exceed 4 mg·kg-1

Table 2. Total cadmium (Cd) content in soil from 2019 to 2021 [$mg \cdot kg^{-1}$soil]

Fertilizer objects	Soil			
	Years			
	2019	2020	2021	Averages
0	0,04	0,05	0,07	0,05
NPK	0,05	0,05	0,07	0,06
M+NPK	0,08	0,06	0,06	0,07
Fc1+N	0,09	0,07	0,08	0,08
Fc5+N	0,06	0,07	0,07	0,07

0 – control object (without fertilization). **NPK** – pre-sowing (N – 100, P – 35, K – 125 $kg \cdot ha^{-1}$), top dressing N – 60 $kg \cdot ha^{-1}$. **Manure+NPK** – Manure 30 $t \cdot ha^{-1}$ i NPK (suplement to the pre sowing NPK dose), top dressing N – 60 $kg \cdot ha^{-1}$. **Pg1+N** – foliar conditioner 1 $t \cdot ha^{-1}$ (N – 100, P – 35, K – 125 $kg \cdot ha^{-1}$), top dressing N – 60 $kg \cdot ha^{-1}$. **Pg5+N** – foliar conditioner 5 $t \cdot ha^{-1}$ (N – 100, P – 35, K – 125 $kg \cdot ha^{-1}$), top dressing N – 60 $kg \cdot ha^{-1}$.

Cadmium belongs to metals that, although produced in significantly smaller quantities than previously mentioned (approximately 20 thousand tons annually) [Niedbała et al. 2010], is often indicated as one of the most dangerous heavy metals for the environment and humans [Żurek and Prokopiuk, 2011]. It is most commonly used in the production of anti-corrosion preparations, specialized paints, pigments for paints, and as a stabilizer in the rubber industry. Cadmium is a metal that is easily taken up by plants, making its concentration proportional to the concentration in the soil matrix [An, 2004; Gołda and Korzeniowska, 2016]. As one of the few metals, it directly affects plants by causing disturbances in photosynthesis [Małkowski, 2011], impairments in CO2 uptake, and indirectly through disturbances in nitrogen compound transformations [Marchner, 1993] and binding with other metals [Carlson, 1985; Starck et al., 1995]. Due to its high toxicity to animals and humans, special attention should be paid to its concentration in animal feeds, and subsequently in meat and plants consumed by humans. Some plants naturally absorb very high amounts of cadmium from the environment, and one of them is tobacco. Therefore, it is considered that the daily cadmium intake for humans is about 20 μg/day, and for smokers of tobacco products, it increases to 35 μg/day

Lead, as one of the most dangerous elements and heavy metals, is still produced in fairly large quantities. Approximately 5.5 million tons are used globally each year in various industries. Although lead is no longer widely used in the refinery industry, it is still extensively utilized in the production of ammunition, alloys, and in the glass and paint industries [Sas-Nowosielska, 2019]. Lead content in plants varies widely, from 0.1 to 30 mg Pb/kg. In addition to accumulating lead from the soil matrix, large amounts are found on the green parts of cultivated plants in the form of fine-grained dust. The highest concentrations are noted not only in areas originally contaminated by industry (Silesia, Lower Silesia, and Małopolska) but also along transportation routes [Niedbała et al. 2010; Wei and Yang, 2010; Żurek and Prokopiuk, 2011; Guo et al., 2012], with special emphasis on railway tracks. Until the year 2000, significant lead contamination was also observed in the vicinity of roads. This was also due to the use of lead tetraethyl-based fuels.

Lead (Pb) is one of the toxic elements occurring in nature. Generally, its mobility in the soil is not high, but with a high content in the soil profile, it is easily taken up by plants [Ciepał, 1992; Terelak et al., 2000]. The lead content in agriculturally used soils should not exceed 100 mg·kg-1. Analyzing the results of total lead content in the soil in the years 2013-2015 (Table 3), significant differences were caused by the applied fertilizers. Also, the conditions prevailing in individual years of research significantly influenced the level of lead content in the soil. Taking into account the averages for fertilization, it should be stated that the significantly highest lead content (4,55 mg·kg-1) in the soil was obtained with the use of fertilization on the Fc1+N combination in relation to the content measured in the soil from the control object. The determined lead content in the soil varied significantly between the years of research. The highest lead content in the soil was recorded in 2019 and amounted to 4.77 mg·kg-1. It was higher than the content measured in 2020 by 0,73 mg·kg-1. Diverse results of the total lead content (Pb) in the soil were also influenced by significant mutual dependencies between the applied fertilization and the years of research.

Table 3. Total lead (Pb) content in soil from 2019 to 2021 [mg·kg^{-1}soil]

Fertilizer objects	Soil			
	Years			
	2019	2020	2021	Averages
0	4,30	3,60	4,17	4,02
NPK	4,32	3,74	4,55	4,20
M+NPK	4,13	3,97	4,41	4,17
Fc1+N	4,77	4,04	4,11	4,31
Fc5+N	4,28	4,14	4,76	4,39

0 – control object (without fertilization). **NPK** – pre-sowing (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Manure+NPK** – Manure 30 t·ha^{-1} i NPK (suplement to the pre sowing NPK dose), top dressing N – 60 kg·ha^{-1}. **Pg1+N** – foliar conditioner 1 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Pg5+N** – foliar conditioner 5 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}.

Table 4. Total nickel (Ni) content in soil from 2019 to 2021 [mg·kg^{-1}soil]

Fertilizer objects	Soil			
	Years			
	2019	2020	2021	Averages
0	2,88	2,86	2,36	2,70
NPK	3,21	2,76	2,63	2,87
M+NPK	2,66	3,88	3,19	3,24
Fc1+N	3,24	3,07	2,62	2,98
Fc5+N	3,12	3,14	2,73	3,00

0 – control object (without fertilization). **NPK** – pre-sowing (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Manure+NPK** – Manure 30 t·ha^{-1} i NPK (suplement to the pre sowing NPK dose), top dressing N – 60 kg·ha^{-1}. **Pg1+N** – foliar conditioner 1 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Pg5+N** – foliar conditioner 5 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}.

Nickel is a heavy metal, and its presence in the soil is mainly associated with its content in the parent material of soils [Kabata-Pendias and Pendias, 1999]. The level of nickel in agriculturally used soils should not exceed 100 mg·kg^{-1}, and depending on its content, its activity in the processes of organic matter decomposition can take the form of an inhibitor or a stimulator. An excess of nickel has a negative impact on the biological activity in the soil [Wyszkowska and Wyszkowski, 2004]. The performed statistical calculations did not show significant changes in the nickel content in the soil under the influence of the studied factors (Table 4). Based on the obtained results, it can be clearly stated that the applied fertilizers on the respective objects led to an increase in the total nickel content in the soil. However, the years of research had a minimal effect on changing the nickel level in the soil [Kalembasa and Symanowicz, 2006].

Nickel is an element with relatively high mobility in ecosystems. The most important system playing a crucial role in its circulation is the soil-plant system. It is usually easily taken up directly proportional to its content in the soil matrix until it reaches a toxic level for maize. This element, in trace amounts, is essential for the proper development of each cultivated plant; however, there are large differences between phytoaccumulation and phytotoxicity for this element [Gambuś, 1997a and b; Spiak, 1996]. There are also various forms in which the occurrence of nickel changes its toxicity coefficient for plants and mutual interactions between cadmium (Cd), copper (Cu), or zinc (Zn) [Kabata-Pendias and Pendias, 1999; Badora, 2002].

The harmful effect of cadmium on plants can manifest as disruptions in the photosynthesis process, alterations in nitrogen compound transformations, and changes in the permeability of cell membranes. In the soil, cadmium in ionic form is rapidly taken up by plants and easily transported through the root system to other plant parts [Symanowicz and Kalembasa, 2011].

As indicated by the research results presented in Table 5, the cadmium content in the roots of the test plant significantly varied under the influence of the applied experimental fertilization. Significant differences in the cadmium content in the roots also emerged in subsequent years of the study. It should be added that mutual interactions between individual fertilizers and years of study significantly affected the cadmium content in the roots of the test plant. The highest average cadmium content in the roots of plants was obtained with NPK mineral fertilization, reaching 0.08 mg·kg^{-1} dry weight. A significant, twofold reduction in the analyzed heavy metal was observed in the roots of objects fertilized with Fc1+N and Fc5+N.

Table 5. Total cadmium (Cd) content in roots from 2019 to 2021 [mg·kg^{-1}soil]

Fertilizer objects	Roots			
	Years			
	2019	2020	2021	averages
0	0,14	0,06	0,07	0,09
NPK	0,12	0,07	0,08	0,09
M+NPK	0,11	0,06	0,07	0,08
Fc1+N	0,06	0,04	0,03	0,04
Fc5+N	0,04	0,05	0,02	0,04

Table 6. Total cadmium (Cd) content in tree from 2019 to 2021 [mg·kg^{-1}soil]

Fertilizer objects	Tree			
	Years			
	2019	2020	2021	averages
0	0,09	0,06	0,10	0,08
NPK	0,10	0,11	0,13	0,11
M+NPK	0,05	0,06	0,07	0,06
Fc1+N	0,02	0,02	0,04	0,03
Fc5+N	0,02	0,03	0,02	0,02

0 – control object (without fertilization). **NPK** – pre-sowing (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Manure+NPK** – Manure 30 t·ha^{-1} i NPK (suplement to the pre sowing NPK dose), top dressing N – 60 kg·ha^{-1}. **Pg1+N** – foliar conditioner 1 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Pg5+N** – foliar conditioner 5 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}.

Regarding the cadmium content in aboveground parts, the applied fertilization and study years had a significant impact in the conducted research (Table 6). Significantly lower cadmium content (twofold) was determined in plants with a reconditioner based on waste brown coal (Fc1+N and Fc5+N). The highest cadmium content was found in maize fertilized with NPK mineral fertilizers. It is presumed that cadmium originated from the mineral fertilizers (superphosphate) applied to the soil.

The intensity of lead uptake from the soil is associated with the presence of organic substances in it [Baran and Turski, 1996]. Low organic matter content in the soil, its acidic pH, and weak sorptive capacities of soils improve the mobility conditions of lead and increase the plant's ability to absorb this element [Terelak and Tujaka, 2003].

Table 7. Total lead (Pb) content in roots from 2019 to 2021 [$mg \cdot kg^{-1}$soil]

Fertilizer objects	Roots			
	Years			
	2019	2020	2021	averages
0	1,81	1,53	1,48	1,61
NPK	1,30	1,28	1,41	1,33
M+NPK	1,30	1,21	1,30	1,27
Fc1+N	1,17	1,06	1,05	1,09
Fc5+N	1,13	1,03	1,05	1,07

Table 8. Total lead (Pb) content in tree from 2019 to 2021 [$mg \cdot kg^{-1}$soil]

Fertilizer objects	Tree			
	Years			
	2019	2020	2021	averages
0	0,27	0,49	0,66	0,48
NPK	0,32	0,58	0,49	0,47
M+NPK	0,48	0,55	0,56	0,53
Fc1+N	0,17	0,16	0,14	0,16
Fc5+N	0,13	0,15	0,12	0,13

0 – control object (without fertilization). **NPK** – pre-sowing (N – 100, P – 35, K – 125 $kg \cdot ha^{-1}$), top dressing N – 60 $kg \cdot ha^{-1}$. **Manure+NPK** – Manure 30 $t \cdot ha^{-1}$ i NPK (suplement to the pre sowing NPK dose), top dressing N – 60 $kg \cdot ha^{-1}$. **Pg1+N** – foliar conditioner 1 $t \cdot ha^{-1}$ (N – 100, P – 35, K – 125 $kg \cdot ha^{-1}$), top dressing N – 60 $kg \cdot ha^{-1}$. **Pg5+N** – foliar conditioner 5 $t \cdot ha^{-1}$ (N – 100, P – 35, K – 125 $kg \cdot ha^{-1}$), top dressing N – 60 $kg \cdot ha^{-1}$.

The research results presented in Table 7 indicate that the lead content determined in the roots of trees from all fertilizer objects significantly decreased compared to the content determined in the roots from the control object. The roots of plants treated with a reconditioner at a rate of 1 t/ha pre-sowing and post-emergence, along with a mineral fertilizer at a rate of 60 kg/ha, exhibited the lowest lead content (1,06 $mg \cdot kg^{-1}$ dry wight). This content was 51,9% lower than the content determined in the roots from the control object. It is presumed that lead was bound in chelate complexes with humic acids from waste brown coal.

The lead content in Paulownia underwent significant changes due to applied fertilization, years of research, and the interaction of fertilization (Table 8). The analysis of average lead contents for fertilization revealed that the highest lead content (0.66 mg·kg-1 dry weight) was found in plants fertilized with manure at a dose of 30 t.ha-1 with NPK fertilizers. Meanwhile, the lowest Pb content was determined in the plant obtained from the Fc5+N fertilization object. It was 2,5 times lower than the lead content measured in the control object plants. Considering the averages for the years of research, significant differences in lead content in aboveground parts were noted between 2013 and 2014 and between 2013 and 2015. The analysis results confirmed that the highest lead content (0,66 $mg \cdot kg^{-1}$ dry weight) was determined in the plant collected from the M+NPK fertilization object in 2014. The application of a reconditioner based on waste brown coal led to a significant reduction in lead content in the plant's dry mass in subsequent years of research [Smolińska and Rowe, 2015].

Table 9. Total nickel (Ni) content in roots from 2019 to 2021 [mg·kg^{-1}soil]

Fertilizer objects	Roots			
	Years			
	2019	2020	2021	averages
0	8,50	8,02	7,60	8,04
NPK	9,00	7,74	8,73	8,49
M+NPK	7,03	7,35	8,01	7,46
Fc1+N	7,64	7,49	7,24	7,45
Fc5+N	7,38	5,81	5,95	6,38

Table 10. Total nickel (Ni) content in tree from 2019 to 2021 [mg·kg^{-1}soil]

Fertilizer objects	Tree			
	Years			
	2019	2020	2021	averages
0	1,64	1,63	1,50	1,59
NPK	1,77	1,75	1,63	1,72
M+NPK	1,05	1,30	1,49	1,35
Fc1+N	1,27	1,59	0,96	1,27
Fc5+N	0,82	0,87	0,92	0,87

0 – control object (without fertilization). **NPK** – pre-sowing (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Manure+NPK** – Manure 30 t·ha^{-1} i NPK (suplement to the pre sowing NPK dose), top dressing N – 60 kg·ha^{-1}. **Pg1+N** – foliar conditioner 1 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}. **Pg5+N** – foliar conditioner 5 t·ha^{-1} (N – 100, P – 35, K – 125 kg·ha^{-1}), top dressing N – 60 kg·ha^{-1}

The average nickel content in the roots of the test plant (Table 9) was at the level of 8.15 mg·kg^{-1} dry weight. Statistical calculations revealed a significant impact of applied fertilization on the nickel level in the roots of test plants. The highest amount of nickel was determined in the roots collected from the object fertilized with NPK mineral fertilizers. This content amounted to 8.73 mg·kg^{-1} dry weight. A significant reduction in nickel content (by 18%) was noted in the roots collected from objects fertilized pre-sowing with a reconditioner at a dose of 5 t/ha-1 and top-dressed with nitrogen at a dose of 60 kg·ha^{-1} in comparison to the content measured in the roots from the control object. Over the years of research, the determined nickel contents in the roots of test plants did not show significant differences (7,93 – 8,33 mg·kg^{-1} dry weight).

The determined nickel contents in the aboveground parts were at a low level [Gorlach, 1991]. As indicated by the research results concerning nickel content in paulownia (Table 10), significant differences occurred under the influence of applied fertilization. Considering the averages for fertilization, the highest nickel content (1,72 mg·kg^{-1} dry weight) was recorded in plants collected from M+NPK, and the lowest (0,87 mg·kg^{-1} dry weight) in plants treated with a pre-sowing reconditioner at a dose of 5 t.ha^{-1} and top-dressed with 60 kg.ha^{-1} of mineral nitrogen.

The translocation of heavy metals in the environment is based on one of the phytoremediation techniques known as phytoextraction—a method used in the remediation of contaminated environments. It relies on the utilization of developed plant processes for the uptake of various substances by the root system and their subsequent transport to the above-ground parts. This is commonly expressed through the translocation index Ti (%), calculated using the formula:

$$\mathbf{Ti = Cb/Ck \cdot 100}$$

where:
Cb - metal concentration in the tissues of above-ground plant organs, mg/kg,
Ck - metal concentration in the root tissues of plants, mg/kg.

These processes allow for the removal of excess harmful substances from the matrix along with the biomass produced during growth. Phytoextraction is most frequently applied in cleaning soil matrices and sediment contaminated with radionuclides [Kondzielski et al., 2003], heavy metals [Kvesitadze, 2006], or organic compounds.

The uptake process itself is commonly expressed through the bioaccumulation factor (also known as the bioconcentration factor – BCF) [Ociepa et al., 2014], calculated using the formula:

$$\mathbf{BCF = Cb/Cg}$$

where:
Cb - metal concentration in above-ground/underground parts of the plant, mg/kg,
Cg - metal concentration in the soil at the beginning of the process, mg/kg.

The calculated values of cadmium (Cd) bioaccumulation coefficients in roots from 2019 to 2021 were significantly diverse depending on the applied fertilization and the respective years of the study (Figure 1). The pre-sowing conditioner based on waste brown coal at doses of 1 and 5t·ha^{-1} with an additional nitrogen dose significantly contributed to reducing the bioaccumulation coefficient values. Significant differences in bioaccumulation coefficient values occurred between the years 2019 and 2020, as well as 2019 and 2021.
As indicated by the results presented in Figure 1, the applied fertilization in the study influenced the significant variation in cadmium (Cd) bioaccumulation coefficients in the aboveground part from 2019 to 2021. Considering the averages for fertilization, the highest coefficient value of 1,90 was calculated for the control object, while the lowest level was achieved for the Fc1+N object.

The obtained coefficients were influenced by both the meteorological conditions during the years of field experiments and the soils on which maize was cultivated. Despite no significant differences, the data presented in Figure 2 indicate a significant impact of the applied fertilization on cadmium translocation coefficients. Conditioners containing organic matter applied to subsequent fertilization objects led to a reduction in translocation coefficients, and the increase in total carbon content in the soil resulted in a decrease in cadmium translocation coefficients.

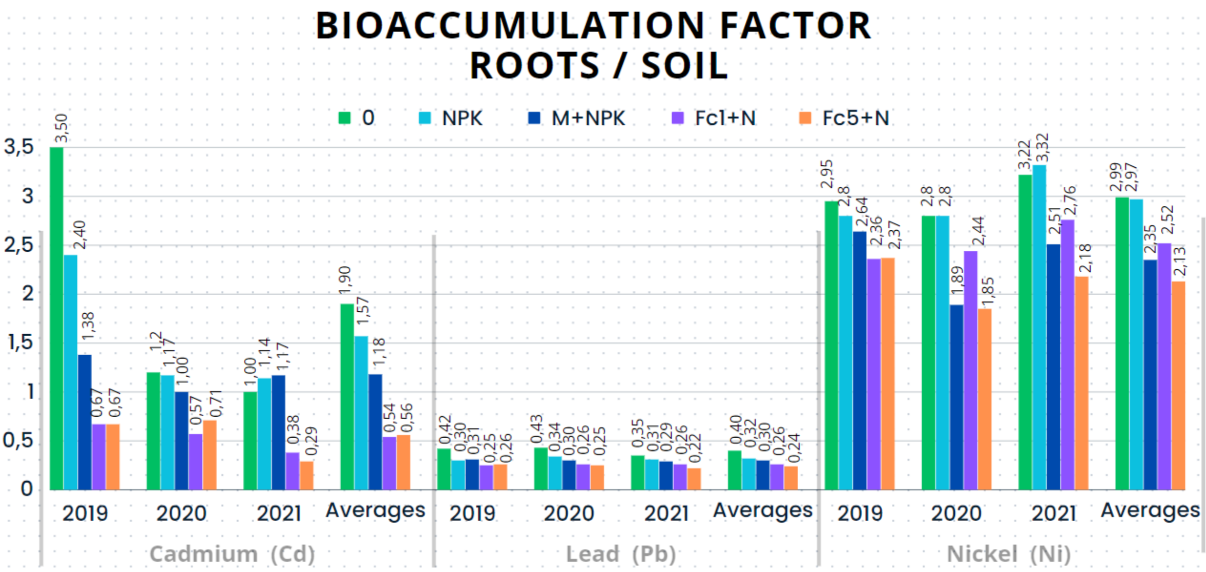

Figure 1. Bioaccumulation Factor of Cadmium, Lead, and Nickel (roots/soil)

Analyzing the numerical data presented in Figures 1 and 2 concerning lead (Pb) bioaccumulation coefficients in roots and aboveground parts, significant differences were demonstrated based on the statistical analysis under the influence of applied fertilization and over the study years. The calculated lead bioaccumulation coefficients in plant roots were consistently high. The values of these coefficients were also influenced by the lead content in both roots and soil. For objects with NPK fertilization in all study years, bioaccumulation coefficients reached the highest values.

Data analysis regarding cadmium translocation in paulownia indicates varied effects of different fertilizer combinations on annual changes in the translocation coefficient of this heavy metal. In 2021, the highest average cadmium translocation was observed for the NPK fertilizer combination, reaching a coefficient of 1,34. During the same period, the Fc5+N fertilizer combination exhibited the lowest average cadmium translocation, at 0,70. Analyzing changes in individual years, a significant increase in cadmium translocation for the NPK combination is evident between 2019 (coefficient 0,83) and 2021 (coefficient 1,63).

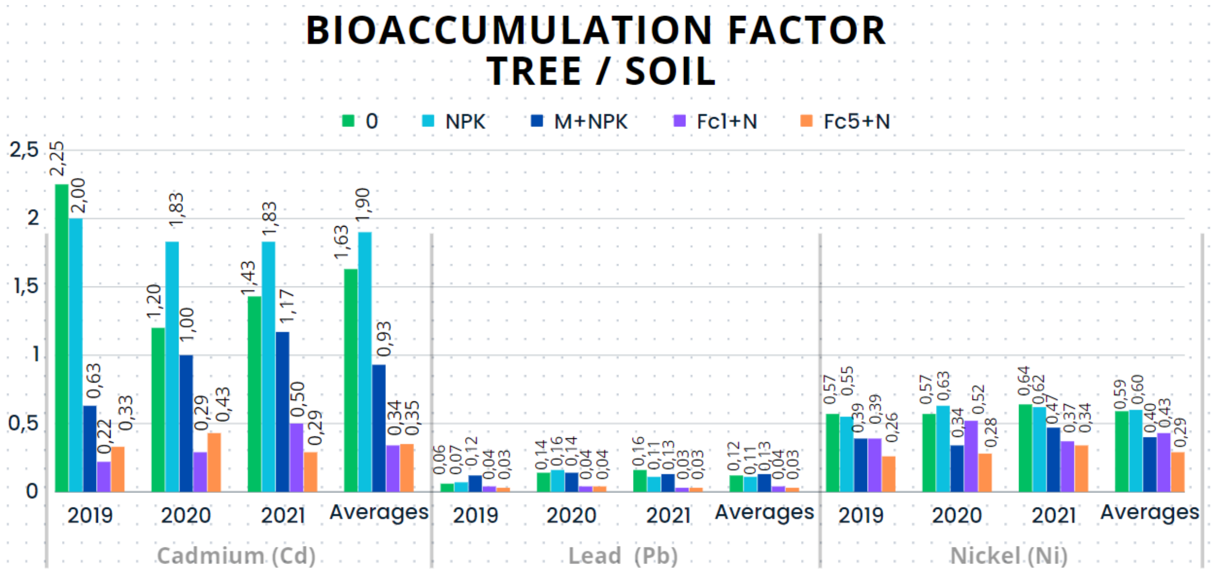

Figure 2. Bioaccumulation Factor of Cadmium, Lead, and Nickel (tree/soil)

The fertilizer combination Fc1+N shows a sharp increase in cadmium translocation from 0,33 in 2019 to 1,33 in 2021. Comparing fertilizer combinations, M+NPK in 2021 had a lower average cadmium translocation (coefficient 0,82), suggesting less effectiveness in transferring cadmium to the aboveground parts of plants. The Fc5+N fertilizer combination also appears to have a lower average cadmium translocation (coefficient 0,70) than the other combinations. The overall trend indicates complex interactions between the applied fertilizers and cadmium translocation. Values above 1,0 indicate a higher amount of cadmium transferred to the aboveground parts of plants than remaining in the soil [Smolińska and Leszczyńska, 2015].

The overall trend suggests an increase in the lead translocation coefficient in paulownia plants over the studied years, indicating enhanced movement of this metal. The M+NPK object seems to exhibit the highest average lead translocation coefficient. It is worth noting that these values varied but generally remained at a high level. On the other hand, the Fc5+N object appears to limit lead translocation, achieving the lowest values, especially in 2021. It is important to note that fertilization models differ in terms of efficiency in controlling lead movement. The M+NPK object may pose a higher risk of increased lead transport, while Fc5+N may be more advantageous.

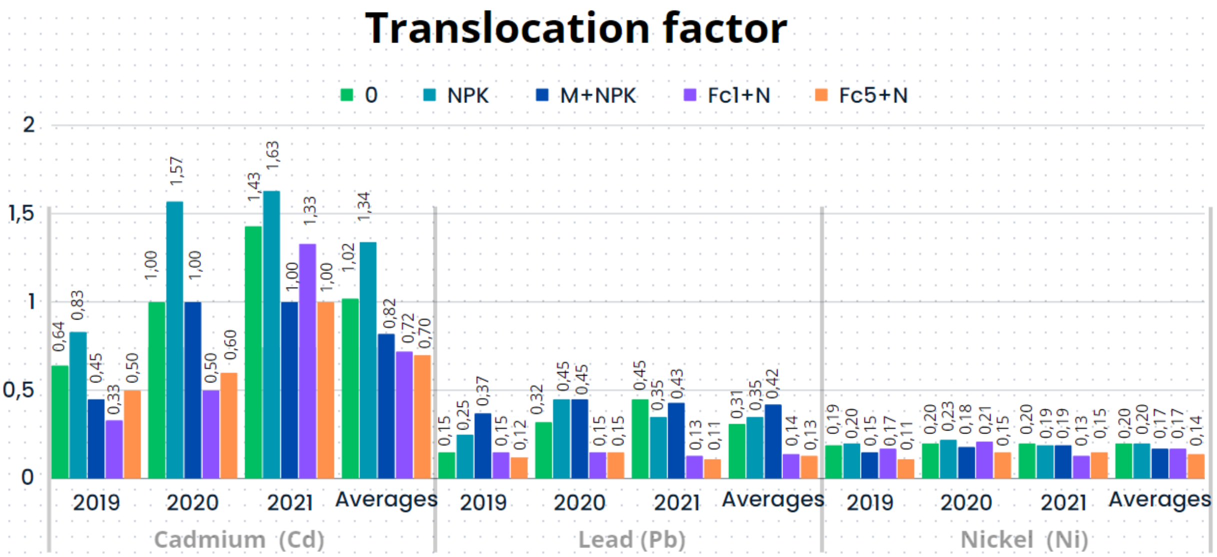

Figure 3. Translocation Factor for Cadmium, Lead, and Nickel

Translate to English: In all types of fertilizers, an increase in the nickel translocation coefficient was observed in 2020 compared to other years (Figure 3). The NPK and M+NPK fertilization models seem to influence higher nickel translocation in the plant, as evident in their average values. The Fc5+N treatment presents a relatively low nickel translocation coefficient (0,14), which may suggest greater efficiency in limiting the penetration of nickel into plants. On the other hand, the Fc1+N model shows significant variability in nickel translocation between years (from 0,13 to 0,21), indicating the influence of environmental conditions. The highest translocation coefficient was recorded for the NPK fertilizer in 2020 (0,23), signaling increased nickel penetration. The Fc5+N conditioner shows the lowest value in 2019 (0,12), suggesting its potential effectiveness in limiting nickel translocation.

CONCLUSIONS

Analyzing the gathered information, we draw more elaborate conclusions regarding the studied plant and the potential application of the conditioner in the phytostabilization process of heavy metals:

Research on paulownia reveals that the effectiveness of phytostabilization of heavy metals in soil strongly depends on the type and dosage of the applied conditioner. The observation that the lowest bioaccumulation coefficients of lead (Pb) and cadmium (Cd) occur for the Fc1+N treatment, and for nickel (Ni) for the Fc5+N treatment, emphasizes the complexity of interactions between the chemical composition of different soil matrix feeding models and the plant's ability to accumulate individual elements.

Observations regarding the translocation coefficients of heavy metals show that the Fc5+N treatment is characterized by the lowest values. This means that the use of this type of feeding and fertilization model may result in limiting the transfer of metals from roots to the above-ground parts of the plant. This is crucial considering that avoiding the translocation of metals can be a significant step towards phytostabilization.

In the context of the conditioner's impact on phytostabilization, we notice that similar bioaccumulation coefficients for the Fc1+N and Fc5+N treatments suggest that the conditioner may play a significant role in maintaining quantitative stability in the absorption of metals by plants. These results suggest that the use of the conditioner may support phytostabilization mechanisms, especially in the case of lead.

Differences in the responsiveness of different metals to fertilization and conditioning highlight the need to consider the specificity of individual elements in planning phytostabilization strategies. In this context, optimizing the phytostabilization process for paulownia requires an individualized approach to the fertilization model and the type of metals present in the soil.

The differences in the responsiveness of different metals to fertilisation and reconditioning highlight the need to take into account the specificity of each element when planning phytostabilisation strategies. In this context, optimising the phytostabilisation process for paulownia requires an individualised approach to the fertilisation pattern and the type of metals present in the soil.

In conclusion, these results indicate that phytostabilization in paulownia is a complex process, requiring consideration of multiple factors such as the type of fertilization, the presence of metals in the soil, and the potential impact of the conditioner. An effective approach to phytostabilization in this context should take these diverse factors into account to optimize the process and achieve the desired results.

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Streszczenie: W ramach niniejszej pracy inżynierskiej głównym celem było zbadanie wpływu rekondycjonerów na translokację i bioakumulację pierwiastków śladowych w drzewie Paulowni. Paulownia, znana jako "drzewo cesarskie", stanowi obiecujący obiekt badawczy w kontekście inżynierii środowiska. Praca koncentrowała się na analizie oddziaływań rekondycjonerów na pierwiastki śladowe w tym gatunku, mając na uwadze aspekty ekologiczne i gospodarcze. Otrzymane wyniki mają na celu przyczynienie się do opracowania skutecznych strategii wspierających zdrowy rozwój roślin, zarówno z perspektywy ochrony środowiska, jak i praktycznego zastosowania w hodowli plantacji Paulowni.

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