

Article

Effect of Plastics (Geotextiles) on Heavy Metal Accumulation by Industrial Hemp Plants Cultivated in Polluted Mediterranean Soils

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Abstract: An attempt was made to simulate the conditions prevailing in an agricultural crop to investigate whether and how geotextile microplastics alter the movement and accumulation of heavy metals in plants. For this purpose, a pot experiment, lasting 149 days, was carried out on soil obtained from a rural area, where pieces of a geotextile in mesoplastic dimensions, of the same chemical composition as that used by farmers in the Greek countryside, were added. Furthermore, metal solutions (Cu, Zn, Cd) were incorporated in the pots at two levels, and incubation prior to planting was carried out for two weeks. Then, industrial hemp was cultivated, while continuous measurements of its horticultural characteristics and of the levels of metals moved from the soil to the plant were made. The plants appeared to be highly resistant to the rather harsh growing conditions, and furthermore, it was observed that the cumulative metal capacity of cannabis was enhanced in most cases. The simultaneous presence of metals and geotextile (plastic) fragments enhanced the amount of Zn and Cd transfer into the soil-to-plant system. Hemp plants exhibited strong resilience abilities in the particularly stressful soil environment, possibly developing defense mechanisms. The experiments are particularly encouraging as they prove that simple and habitual practices in cultivated soils that lead to post-weather erosion of the geotextile may contribute positively in terms of remediation methods for heavy-metal-laden soils, as they indirectly help the plant to remove larger amounts of metal elements. The experiments should be intensified on a wider range of soils of different soil reactions and particle sizes and, of course, should be carried out under real field conditions in Mediterranean soil environments.

Keywords: hemp; potentially toxic elements; geotextile; phytoremediation



Academic Editor: Adriano Sofò

Received: 21 April 2025

Revised: 19 May 2025

Accepted: 19 May 2025

Published: 20 May 2025

Citation: Alexiadis, D.; Bethanis, J.; Papadimou, S.G.; Barbieri, E.; Vogia, R.; Tatsi, E.; Tziourrou, P.; Tsaliki, E.; Golia, E.E. Effect of Plastics (Geotextiles) on Heavy Metal Accumulation by Industrial Hemp Plants Cultivated in Polluted Mediterranean Soils. *Int. J. Plant Biol.* **2025**, *16*, 53. <https://doi.org/10.3390/ijpb16020053>

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1. Introduction

Heavy metals have constituted a crucial soil and hence environmental issue in recent decades, as they pose potential risks [1]. Their numerous and diverse uses, their long residence time in the environment and their high accumulation are factors that could be of concern to environmentalists [2]. They can be easily transferred from air pollutants to soil and from the soil to water, both surface water and water in underground aquifers [3]. Their presence in soil and the relatively easy movement to both native and cultivated plants is an

additional concern, as they can be a negative burden on edible plants. Notably, it is known that they frequently pose a risk to human health [4]. Researchers Das et al. [5] describe a wide range of plants and their potential health risks to humans due to their consumption in detail.

Many methods have been proposed and used to remove or reduce their concentration in soils, both in urban and rural soil environments, with phytoremediation being one of the most tempting proposals [6]. Numerous plant species have developed defense mechanisms against heavy metal toxic environments and are able to grow smoothly and without particular impairment or loss of yield [7,8]. Vasilou et al. [9] found that industrial hemp (*Cannabis sativa* L.) has been shown to be able to accumulate metals in significant quantities in its tissues without significantly altering its quality characteristics and without reducing the production of its valuable secondary metabolites (CBD, THC). Monrroy et al. [10] found that *Cajanus cajan* growth did not appear to be affected by the high metal concentrations, even when the metals were present in combination with each other. In most cases, the accumulation of metals was observed in the root, indicating that phytostabilization is probably the main mechanism of soil remediation [11]. Małecka et al. [12] discussed the defense mechanisms of *Brassica juncea* in order to accomplish its development in a multi-element soil environment. Furthermore, Alsafran et al. [13] studied and presented a series of plant-activated mechanisms in order to cope with heavy metal toxic soil environments, highlighting a new approach through amino acids binding to micronutrients.

Plastics, including geotextiles, apart from heavy metals, represent a new emerging risk, as depending on their dimensions and chemical composition, they may be able to enter plants and, through them, perhaps reach humans [14,15]. Leitão et al. [16] found microplastics in the urban topsoils of Coimbra city, and they studied their spatial distribution. In agricultural soils, Deng and his colleagues [17] thoroughly investigated microplastic dynamics as they compared data over a thirty-year study.

The simultaneous presence of heavy metals and several kinds of plastics in agricultural and urban soils is common, and research is ongoing, as a variety of chemical reactions and physicochemical interactions can change soil properties and metal availability and thus the degree of risk [18]. Pinto-Poblete et al. [19] showed that the simultaneous presence of Cd and high-density polyethylene (HDPE) in microplastic dimensions causes several changes, both in plant growth and metal accumulation by strawberry plants. Furthermore, Chen et al. [20] found that polystyrene microplastics may pose a fundamental risk to *Vicia faba* plants, highlighting that both the chemical composition and the dimensions of plastics can have different impacts on the soil chemical properties as well as on crops. Zhang et al. [21], in their research, concluded that the presence of polystyrene microplastics along with Cd enhanced photosynthetic capacity in *Brassica chinensis* L. plants. Bethanis and Golia [22] found that the coexistence of polyethylene microplastics along with two metals (Zn and Cd) can alter soil pH, affecting metal accumulation in plant tissues. Both Cao et al. [23] and Kumar et al. [24] thoroughly studied and meticulously presented the possible mechanisms developing between heavy metals and different types of microplastics, including polypropylene (the main plastic existing in geotextiles), when they coexist, creating and intensifying the toxic polluted environment.

Plants' biological response to stresses following changes in the physicochemical properties of soils has been studied [25]. The study of antioxidant defense mechanisms in plants under abiotic stresses like salts was the main purpose of the study of Ahmad et al. [26]. As concluded by Ghori et al. [27], plants can produce methylglyoxal (MG) (a reactive $\alpha\beta$ -dicarbonyl aldehyde) as a response to various stresses. Researchers Ningombam et al. [28], in their study, tried to decipher heavy metal stress resilience in plants using physiological, biochemical, molecular and omics mechanisms. As this research has shown, most

plant species have developed defense strategies and mechanisms, such as phytochelatin sequestration and powerful antioxidant regimes, to meet these challenges. Furthermore, Ji et al. [29] studied the dual and ancillary influence of microplastics and cadmium toxicity on both the microbial population as well as on the soil-derived organ systems of the wheat rhizosphere.

Furthermore, the production of secondary metabolites of high economic importance, such as syllimarin, at higher rates has been observed when the plant is grown in a highly toxic heavy metal environment [30]. It is therefore very important to investigate the effect, both on the rate of soil-to-plant metal translocation and the number of secondary metabolites produced, of the simultaneous presence of both heavy metals and plastics in specific dimensions and chemical compositions.

The objective of the present research was to investigate the effect of geotextiles, used to cover cultivated soils, on the metal accumulation capacity of industrial hemp in conditions simulating its customary cultivation in Mediterranean soils contaminated by Cu, Zn and Cd.

2. Materials and Methods

2.1. Methodological Framework: Experimental Setup

Three metals were chosen for this experimental procedure, namely copper (Cu), zinc (Zn) and cadmium (Cd). For Cu solutions, levels A and B were set at 140 and 280 mg Cu kg⁻¹ of dry soil, respectively; for the Zn solutions, levels A and B were set at 300 and 600 mg Zn kg⁻¹ of dry soil; and for the Cd solutions, it was decided that levels A and B would correspond to 3 and 6 mg Cd kg⁻¹ of dry soil, respectively. The initial metal concentrations were as follows: 10, 15.6 and 0 mg kg⁻¹ of Cu, Zn and Cd, respectively. The components used for A and B levels for Cu, Zn and Cd were Cu(NO₃)₂·3H₂O, Cd(NO₃)₂·4H₂O and Zn(NO₃)₂·6H₂O, respectively; the levels were chosen in accordance with the European Union's maximum allowed concentrations and their doubles [6,9]. It was decided that the treatments to be applied would be the following: Soil, Soil + Geotextile, Geotextile + Cu A, Geotextile + Cu B, Geotextile + Cd A, Geotextile + Cd B, Geotextile + Zn A, Geotextile + Zn B, Geotextile + Cd + Cu, Geotextile + Cu + Zn, Geotextile + Zn + Cd, Geotextile + Cu + Cd + Zn. These treatments were repeated without the presence of geotextile.

The rural soil sample, which was collected from the ELGO-DIMITRA farm (Thessaloniki, Greece), was air-dried and sieved (using a 2 mm sieve) to remove stones and other transported materials and residues in preparation for contamination. Geotextile fragments in mesoplastic dimensions (5 to 20 mm) were added to the soils. The geotextile used has a chemical composition of polypropylene (85%) and cotton (15%). Geotextile fragments were carefully washed using NaClO 0.01 M solution to reduce any microbial activity [31]. Finally, the metal solutions were added and mixed with 7.5 kg (for each pot) of soil in black plastic bags, where the soil-heavy metal mixture remained for 15 days (as a pre-incubation period before planting), with the bag sealed, while being stirred at regular intervals. The pots were watered before planting to keep their humidity at about 70%. After the incubation period, Fedora 17 hemp (a monoecious variety with a plant cycle of 129 to 134 days (as a threshed crop), reaching a mature height between 6'5" and 8'25" and yielding approximately 3.5 to 4.5 tons of biomass per acre) seedlings were transplanted along with the treatments. Specifically, 5 (five) plants were placed in each pot. In total, there were 36 pots, corresponding to 12 treatments with 3 replications each.

2.2. Laboratory Analyses

The determination of the soil samples' pH was carried out in a soil-water suspension at a 1:2.5 ratio [32]. The pH was measured using a BASIC 20+ pH meter (Crison Instruments SA, Barcelona, Spain). The EC measurement was estimated in μS cm⁻¹ using the EC-meter

BASIC 30+ conductivity meter (Crison Instruments SA, Barcelona, Spain). The soil texture was determined using the hydrometer method (also known as the Bouyoucos method) [33]. The percentage content of calcium carbonate (% *w/w* CaCO₃) in the soil was determined using a calcimeter, following the procedure of Allison and Moodie [34]. The plant samples were cleaned with distilled water and then dried at 75 °C and ground using an electric mill and/or porcelain mortar and pestle, and the powdered samples (both shoots and roots) were stored separately for laboratory analyses. From the aboveground part of the stem, the leaves were also stored separately after drying, as was the inflorescence (flowers). To determine the pseudo-total concentrations of Cu, Cd, and Zn, extraction of the soil and plant samples was performed using aqua regia, a 3:1 ratio of concentrated hydrochloric acid (HCl) and concentrated nitric acid (HNO₃) [35]. The pseudo-total metal concentrations were then determined using a flame atomic absorption spectrophotometer (AAS), using an AA-6300 Shimadzu 6300 (Tokyo, Japan) device.

2.3. Statistical Analysis

Soil samples were collected from each pot in the experiment, i.e., from each treatment (pots were in triplicate). The chemical analyses for each sample were conducted in 5 replicates. The values shown in the tables and graphs represent the mean values. For data analysis, one-way analysis of variance (ANOVA) was performed for each polymer and soil type, according to the normality of the data. In particular, the polymer quantity was the factor, while for mean comparison, Fisher's least significant difference (LSD) test at $p < 0.05$ was employed. Diagrams depict standard error bars, a graphical representation of data variability used to indicate the error or uncertainty in a reported measurement. All analysis was conducted using the SPSS statistical package (IBM SPSS Statistics 26) and Microsoft Office Excel.

3. Results and Discussion

3.1. Physicochemical Properties of Soil Samples

Table 1 presents the physicochemical characteristics of the soil sample used in this experiment.

Table 1. Values of physicochemical properties of soil samples ($n = 5$).

	pH (1:2.5)	EC ($\mu\text{S cm}^{-1}$)	OM (%)	CaCO ₃ (%)	Clay (%)	Texture
Minimum Value	7.48	457	2.62	12.2	39	Clayey
Maximum Value	7.77	553	3.18	14.3	44	
Mean Value	7.61	498	2.91	13.3	41	
Relative Standard Deviation (%)	2.2	10.7	1.1	1.7	0.9	

In Table 1, it is obvious that the soil characteristics used in the experiment match those of cultivated agricultural soils in Greece [6,36]. Greek soils are characterized by relatively low organic matter content and, for the most part, exhibit an alkaline reaction [6,30]. In Table 2, the physicochemical properties of the soil samples after the addition of the plastics with the dimensions of mesoplastics and their incubation for a period of 149 days (until the end of the experiment) are presented.

Table 2. Soil physicochemical properties after plastic addition (end of experiment).

	pH (1:2.5)	EC ($\mu\text{S cm}^{-1}$)	OM (%)	CaCO ₃ (%)	Clay (%)	Texture
Minimum Value	6.61	344	3.1	12.2	39	Clayey
Maximum Value	7.83	905	3.7	14.3	44	
Mean Value	7.37	512	3.2	13.3	41	
Relative Standard Deviation %	1.9	8.9	1.5	1.6	1.1	

By comparing Tables 1 and 2, it is evident that the pH value tends to decrease (acidify), as the average pH of the samples has dropped by 0.24, while the minimum value has decreased by 0.87 units. However, it is also observed that there is a slight increase in the maximum pH value of 0.06. The EC of the soil samples appears to show an increasing trend, with an average value now at $512 \mu\text{S cm}^{-1}$. At the same time, the range between minimum and maximum values has widened further, with a maximum of $905 \mu\text{S cm}^{-1}$ and a minimum of $344 \mu\text{S cm}^{-1}$. It is also noteworthy that an increase in the OM content of the soil samples has been observed. Adding materials to soils is expected to result in changes in the physicochemical properties of the soils. The addition of plastics modifies both physical and chemical properties as a number of changes are triggered by their presence [14]. Their addition, depending on their dimensions, can cause a change in the drainage soil capacity, so several reactions that take place in anaerobic environments can be activated [37]. The chemical composition of plastics is a key factor as it can also cause changes in the soil reaction. Bethanis and Golia [22] found that the presence of polyethylene eventually causes a decrease in soil pH, while Li et al. [38] found that the presence of polypropylene and polyvinyl chloride microplastics in soils also causes a slight acidification after a three-month experiment.

3.2. Levels of Cu in Plant Tissues

Figure 1 depicts the Cu concentrations in the roots, stems and flowers of the hemp plants.

It is noted that in all cases, the root Cu concentration in the treatments with geotextile addition is higher than in the corresponding ones without it. Geotextile addition aided in Cu absorption by the roots of cannabis. For the Cu concentration in the hemp roots in the single-element soil addition, it was observed that there was a statistically significant difference compared to the multi-element soil contaminations, as well as between the treatments with and without the geotextile.

On the other hand, Cu in hemp stems, in the treatments with plastic, is almost equal to that without its presence. However, the absorption values are much closer to each other and are grouped in pairs, except for the Geo + Cu B and Soil + Cu B treatments. In both cases, with and without the geotextile, it was observed that the greater movement of Cu towards the plant's stem occurred when the contamination was with a single element (in the cases of Soil + Cu A and Geo + A). It should also be noted that 6 out of the 12 treatments (50%) showed no statistically significant differences among them. Cheng et al. [25], in their study, focused on the ways hemp can respond adequately to Cu stress in the soils where it is grown. Although both plant development and biomass decreased, it was observed that lipids and enzymatic antioxidants increased. In addition, proper supplementation of fertilizers helped the growth of the produced mass, reducing potential membrane injury.

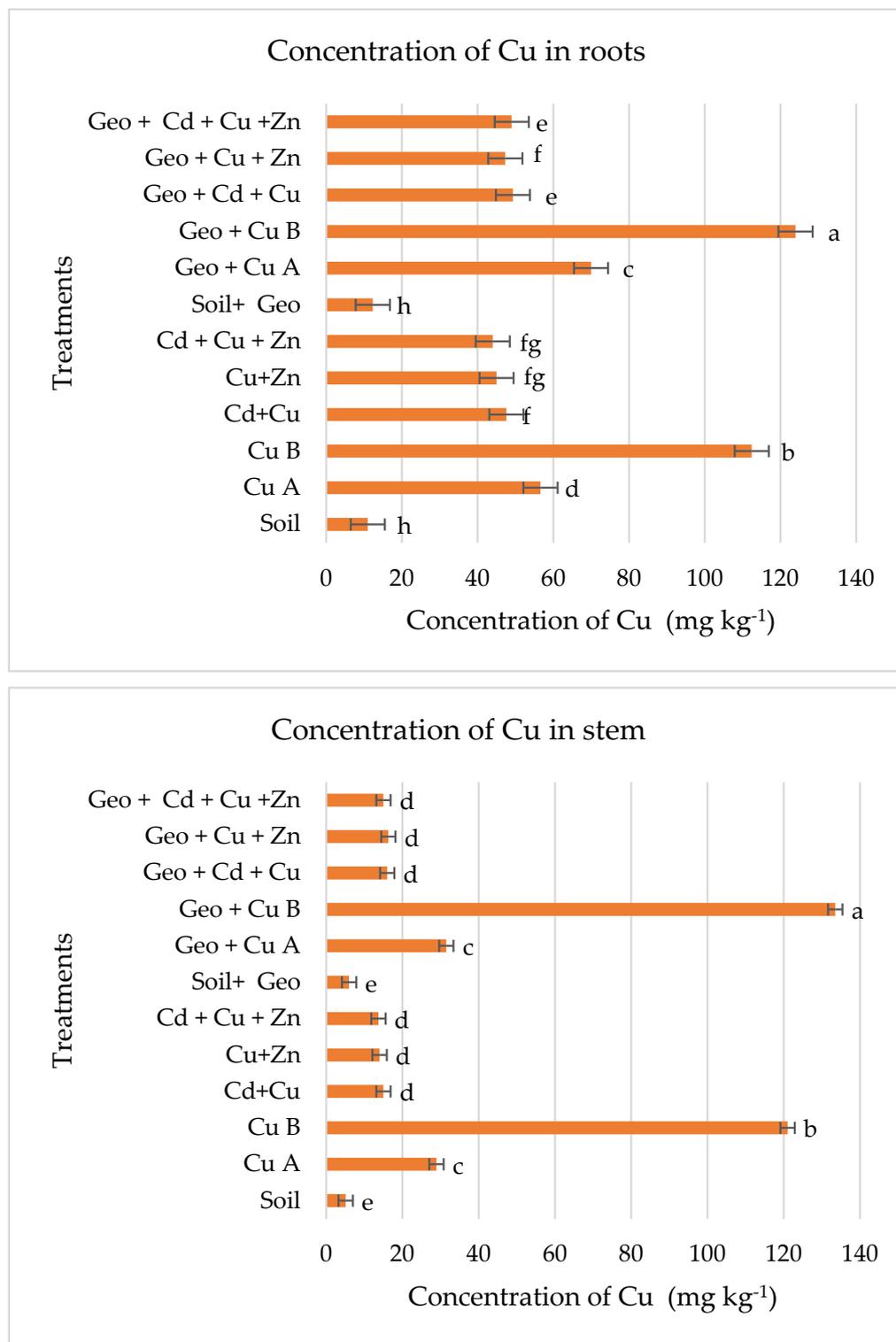


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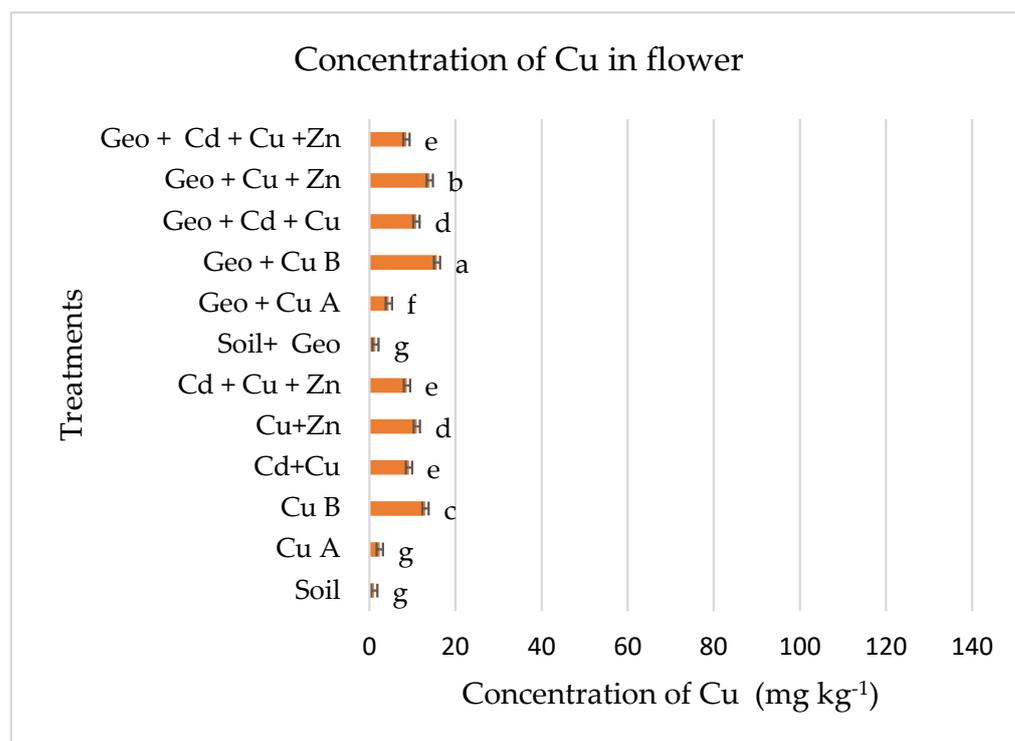


Figure 1. Comparison of Cu concentrations in hemp tissues with and without plastic. The different letters (a–h) indicate statistically significant differences between treatments.

Cu concentration in hemp flowers is higher in the treatment with the geotextile, with the only exception being the Geo + Cu + Cd + Zn treatment, which has a concentration 0.1 mg kg^{-1} lower than the corresponding treatment without the geotextile (Soil + Cd + Cu + Zn).

It can be concluded that the geotextile helps in the movement of Cu to the flowers of cannabis. It was also observed that there was a higher concentration of Cu in the Geo + Cu + Zn treatment compared to the treatment where Cu was added at the B level (as previously defined) without the presence of the geotextile.

Additionally, single-element soil contaminations tend to have a greater impact on Cu concentrations in the aboveground part of the plant than multi-element contaminations. The single-element soil contaminations do not show significant differences between them regarding Cu movement from the root to the upper parts of the plant. Likewise, the multi-element contaminations do not show statistically significant differences within each treatment pair or when compared with other treatment pairs. Therefore, a metal combination in soil systems, with or without the presence of the geotextile, is the key factor that determines Cu accumulation by the upper parts of the plant.

Table 3 depicts Cu concentrations ratios in hemp parts with and without geotextile.

Cu ratios in the plant parts are relatively close within treatment pairs (without and with the geotextile), though it should be noted once again that the absolute concentrations in the geotextile treatments were higher. The ratios within each treatment pair, across all plant parts (root, stem, flowers, aboveground part), are numerically close. In the roots, it was observed that, relative to the respective soil for each treatment, more Cu was absorbed in the absence of the geotextile where a combination of metals was present. However, this does not necessarily mean that the total quantity of Cu absorbed was greater. In the case of single-element contamination with Cu, there was slightly higher proportional Cu uptake. As for the stems, a greater ratio of Cu translocation from the roots was again observed in the treatments without the geotextile. The ratios were, once more, numerically close, except possibly in the treatments where Cu was added at level B. In the flowers, the ratios

were again close, except perhaps in the treatments with Cu addition at level A and the multi-element addition of Cu + Cd + Zn. Golia and Liava [31] found that the coexistence of polyethylene (PE) or polyethylene terephthalate (PET) microplastics along with potentially toxic metals can alter agricultural soils' health.

Table 3. Ratios of Cu concentrations in plant parts in the treatment with and without plastic, compared to Soil and Soil + Geotextile.

Treatment	Root Concentration Ratio	Stem Concentration Ratio	Flower Concentration Ratio	Above-Ground Concentration Ratio
Soil	1.00	1.00	1.00	1.00
ZnA	5.16	5.66	2.18	5.22
ZnB	10.3	23.7	11.8	22.2
Cu + Zn	4.34	2.94	8.36	3.62
Cd + Zn	4.10	2.74	10.0	3.65
Cd + Cu + Zn	4.01	2.68	7.91	3.34
Soil + Geo	1.00	1.00	1.00	1.00
Geo + ZnA	5.69	5.25	3.24	4.98
Geo + ZnB	10.1	22.3	11.3	20.8
Geo + Cu + Zn	4.01	2.67	7.84	3.36
Geo + Cd + Zn	3.85	2.72	10.1	3.70
Geo + Cd + Cu + Zn	3.98	2.50	6.19	2.99

Although the presence of the geotextile in the soil enhances the absorption and translocation of Cu within *C. sativa* L., it may reduce the maximum proportional Cu uptake from the soil. To confirm this observation, further research is required to determine the maximum potential Cu absorption by the plants. This would help exclude the possibility that the lower ratios in the presence of the geotextile are due to the plant's inability to absorb additional Cu, since the experiment has shown that Cu absorption and translocation are greater in the presence of the geotextile in cannabis plants. Gu et al. [39], in their research on *Vetiveria zizanioides*, proved that when inoculated with AMF, it grew without difficulty at high Cu concentrations, responding completely to all stress levels. The study of defense mechanisms for Cu, as well as in various other metals, will undoubtedly be a subject of future research in our experiment.

3.3. Levels of Zn in Plant Tissues

Figure 2 depicts the Zn concentrations in the roots (a), stems (b) and flowers (c) of the hemp plants.

Figure 2 displays the Zn concentration values accumulated in the plant tissues when the geotextile was added and when single- and multi-element solutions containing the three metals included in the study were added. Both in the aboveground part, i.e., stems and leaves, as well as in the root, geotextile presence seems to enhance the accumulation of Zn in the plant, as the concentration values were higher in the presence of the geotextile than when the geotextile was absent. Metal concentration, likewise, is the key factor that determines the amount of metal transport into the soil-to-plant system. That is, at the B contamination level, the concentrations of metals transferred to the different parts of the plant were higher than the corresponding concentrations at the A contamination level. Sabir et al. [40], in their research, reached the same conclusion after studying the transport of five heavy metals from soil to *Alhagi maurorum* Medic., *Astragalus creticus* Lam., *Cichorium intybus* L., *Berberis lycium* Royle and *Datura stramonium* L. plant tissues.

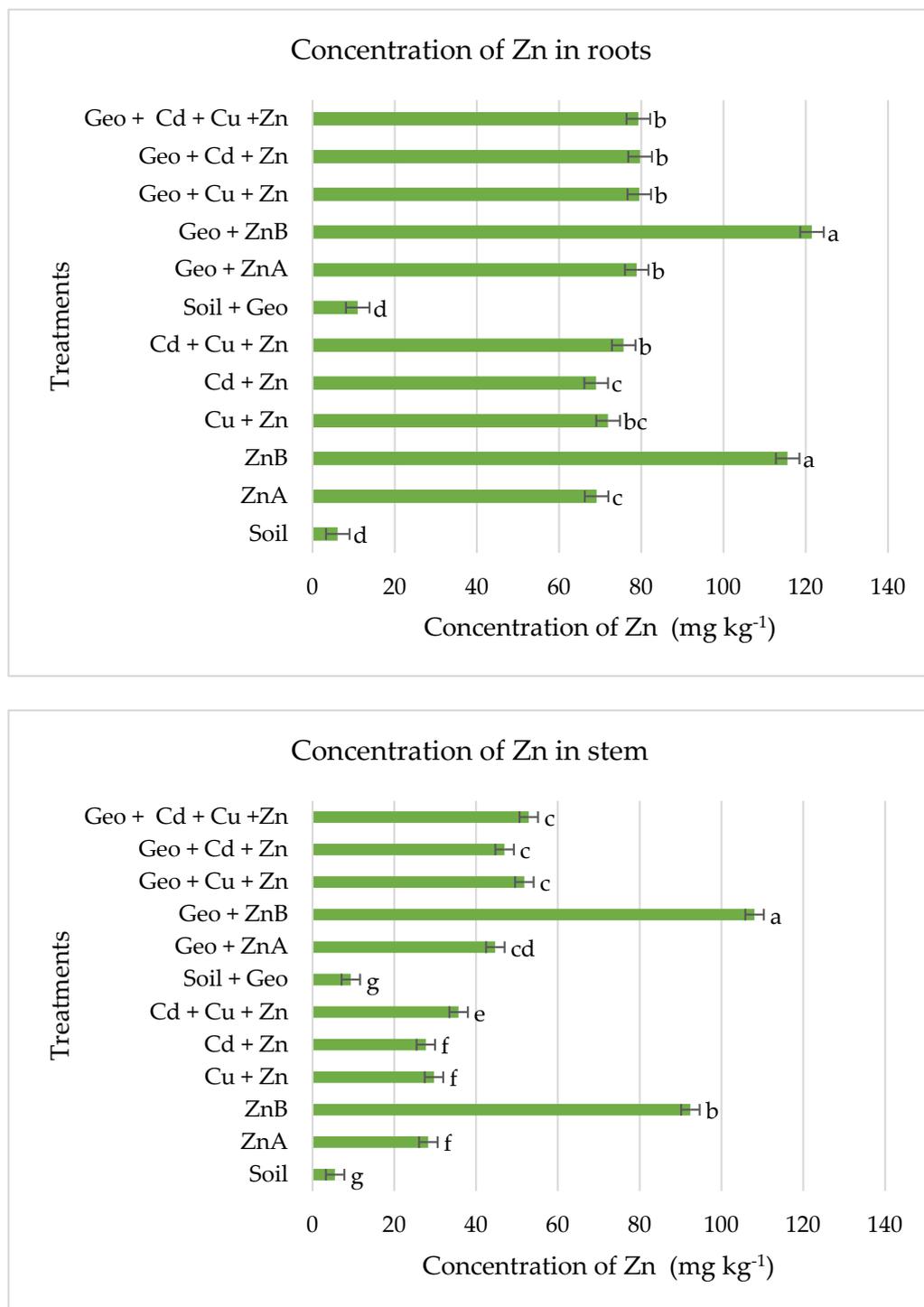


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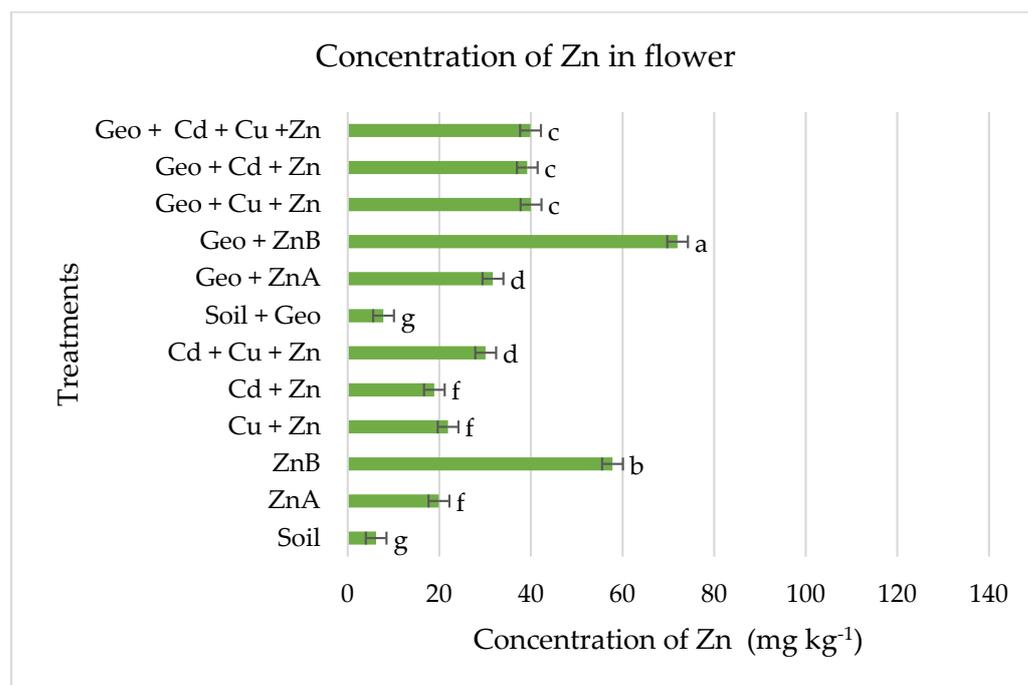


Figure 2. Comparison of Zn concentrations in hemp tissues with and without plastic. Different letters (a–g) indicate statistically significant differences between treatments.

In treatments where the geotextile was added under multi-metal contamination, it was noted that the coexistence of Geo + Zn + Cd in the soil reduced the Zn concentration in the hemp stem. However, no statistically significant differences were observed compared to the corresponding treatments that were contaminated either with single-metal or multi-metal solutions in the presence of the geotextile. In the absence of the geotextile in soil polluted with all three metals, the Zn concentration in the plant stem was higher than that observed in the metal combination or single-metal treatments, and statistically significant differences were noted between the treatments.

The Zn concentration in hemp flowers is higher after geotextile addition. In the individual treatments with the geotextile, it was observed that the multi-element contamination of the soil has a statistically higher concentration of Zn than the single-element one (Geo + Zn A), which, however, still has a statistically significant difference compared to the treatments without the geotextile, except for the treatment that contains all three metals (Soil + Cu + Cd + Zn). In the flowers, it was additionally observed that there is also a statistically significant difference between the contaminations at level B. It can be concluded that the geotextile has a positive effect on the translocation of Zn to the flowers of cannabis. It should be noted that Zn concentrations were highest in the roots in all cases, followed by concentrations in the stems. Lower concentrations were found in the leaves of the plant, in the upper part of the plant.

In Table 4, Zn concentrations expressed as concentration ratios compared with the control soil sample are presented.

In Table 4, the ratio of Zn concentrations in various plant parts of the treatments is shown, using the Soil and Soil + Geo as baseline ratios for treatments without and with the geotextile, respectively. If one looks closely at the ratios, it can be observed that in treatments without the geotextile, there seems to be a higher Zn absorption. However, it should be considered that the initial heavy metal absorption concentrations in all plant parts were higher in the treatments with the additional plastic burden. This means that the actual Zn absorption by hemp was higher in the treatments with the geotextile. Regarding the treatments with levels A and B of Zn contamination, it was observed that where the

geotextile was present, there was a smaller difference between the two ratios, meaning that the plant could absorb and transfer Zn more effectively to its various parts, even when its concentration in the soil was lower. The researchers Anisimov et al. [41], in their research, reached almost the same finding by examining Zn transfer from soil to plant tissues. Furthermore, the pool of labile Zn compounds has been determined after the proper calculations.

Table 4. Ratios of Zn concentrations in plant parts in the treatment with and without plastic, compared to Soil and Soil + Geotextile.

Treatment	Root Concentration Ratio	Stem Concentration Ratio	Flower Concentration Ratio	Above-Ground Concentration Ratio
Soil	1.00	1.00	1.00	1.00
ZnA	11.3	5.14	3.21	4.31
ZnB	18.8	16.8	9.32	13.58
Cu + Zn	11.7	5.39	3.53	4.60
Cd + Zn	1.24	5.03	3.05	4.18
Cd + Cu + Zn	12.3	6.48	4.85	5.78
Soil + Geo	1.00	1.00	1.00	1.00
Geo + ZnA	7.17	4.77	4.06	4.52
Geo + ZnB	11.0	11.5	9.23	10.7
Geo + Cu + Zn	7.23	5.53	5.13	5.39
Geo + Cd + Zn	7.24	5.01	5.03	5.02
Geo + Cd + Cu + Zn	7.21	5.65	5.12	5.46

It is noteworthy that the concentration ratios in the root are smaller in the treatments with the geotextile, while in the flowers, they are higher. Regarding the stems, a large difference was observed in the treatments at the B-level addition, and in the part we designated as aboveground, the ratios are similar. From all the above and the statistical analysis (Figure 2), it can be concluded that the cannabis plant shows increased Zn absorption in the presence of the geotextile, but there is an analogous similarity in its ability to absorb Zn when the geotextile is not present, whether the Zn is in the soil as a single-element contamination or as a multi-element contamination. Asare et al. [42] studied the mechanisms of Zn movement (influx/outflow) in plants capable of accumulating metals. Zn ion movement hinged on genotypes biochemically linked to carrier proteins in different compartments. Available Zn cations move via apoplastic and symplastic root pathways, translocating to the xylem and finally to the phloem.

3.4. Levels of Cd in Plant Tissues

Figure 3 depicts the Cd concentrations in the roots, stems and flowers of the hemp plants.

As shown in Figure 3, it was observed that all treatments, except for those involving Cd addition at level B (as defined), both with and without the geotextile, do not statistically significantly differ from each other. This leads to the conclusion that the presence of other metals such as Cu and Zn in the soil does not affect the ability of cannabis plants to absorb Cd in their roots. In addition to this observation, it was also found that the presence of the geotextile does not create statistically significant differences in Cd uptake when Cd is at low soil levels.

Cd uptake in hemp stems was not strongly influenced by the presence of the geotextile. It should again be mentioned that no Cd was found in the treatments where the soil had not been contaminated with it. Within each treatment pair, a higher amount of Cd was consistently found in cases where the geotextile was present. Cd was not transported from the root system and the stem to the flowers in most cases, except for three. In all three cases, there was a statistically significant difference in Cd concentration. During the experiment,

there were speculations about whether Cd would be detected in the flowers of the plants, and it was proven that it is transferred there only at very high concentrations.

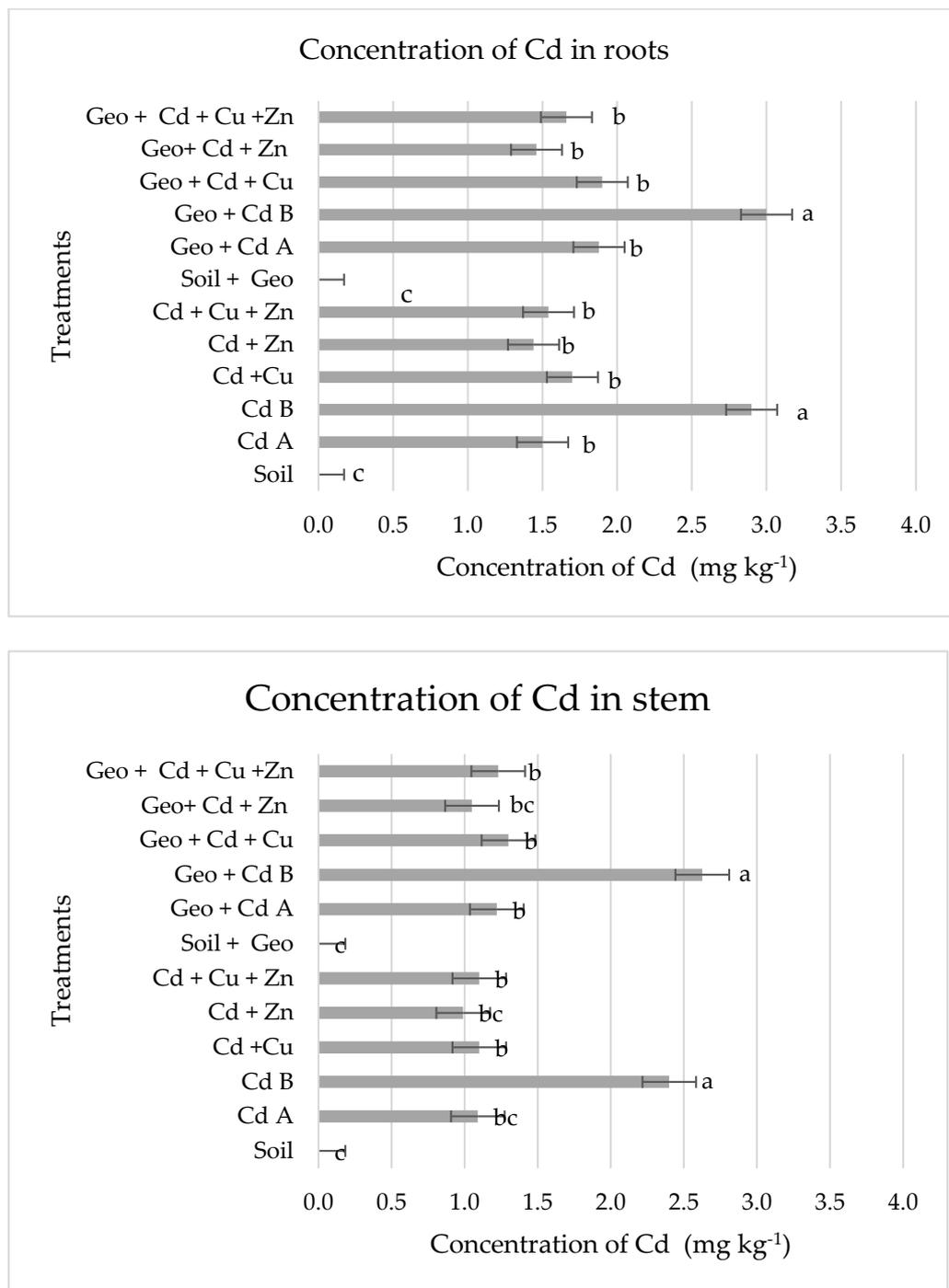


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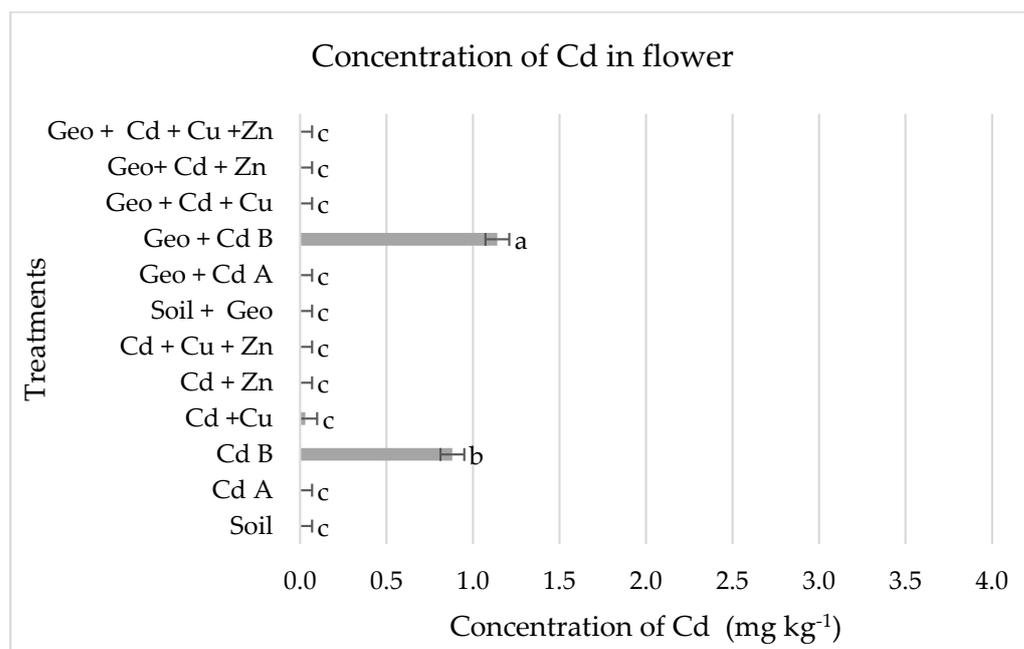


Figure 3. Comparison of Cd in hemp tissues with and without plastic. The different letters (a–c) indicate statistically significant differences between treatments.

For Cd in the above-ground part (as defined) of the plants, it was observed that there are no statistically significant differences between the treatments where there was single-element or multi-element soil contamination. Furthermore, it appeared that the presence of the geotextile in the soil does not constitute a factor that would influence the translocation of Cd to the upper parts of the plant when Cd is at low soil levels. A Cd uptake ratio table could not be created as no Cd was found in the non-contaminated treatments (Soil, Soil + Geotextile).

According to the study by Xu et al. [43], the presence of polyethylene microplastics (PE-MPs) significantly affected the accumulation of Cd in the wild tomato plant (*Solanum nigrum*). The study found that high doses of PE-MPs inhibited plant growth, reducing its overall biomass. At the same time, the concentration and accumulation of Cd decreased, a fact associated with the alteration of its bioavailability in the soil. The PE-MPs caused a reduction in the available amount of Cd in the rhizosphere, possibly due to interactions with the C-H and -COO functional groups formed in the soil. In addition, the simultaneous exposure to Cd and plastics caused metabolic changes in the plant. The biosynthetic processes related to carbohydrates and adenosine were significantly suppressed, which may affect the overall physiological response of *Solanum nigrum* under pollution conditions. Overall, the coexistence of Cd and microplastics reduced the plant's ability to accumulate Cd, which may affect its effectiveness as a phytoremediator for heavy-metal-contaminated soils. An et al. [44] investigated how the size of microplastics (PS-MPs) affects the movement and toxicity of Cd in a soil–bok choy (*Brassica rapa*) system. Microplastics with a size of 0.2 μm did not significantly affect the uptake of Cd by the plant, whereas those of 2 and 20 μm led to a significant reduction in Cd mobility in the soil, which in turn reduced its uptake by bok choy. Moreover, the 2 and 20 μm microplastics caused a notable decrease in Cd accumulation in the plant, with reductions ranging approximately from 20% to 47% in leaves and roots, while they also modified Cd distribution in the plant parts. Finally, the addition of 2 and 20 μm microplastics improved the growth of bok choy, as increases in length and dry mass were observed, along with a decrease in oxidative stress indicators and other biological signs of damage, indicating that these microplastics can mitigate Cd

toxicity. In the study of Liu et al. [45], a possible explanation is that *Cannabis sativa* L. is probably able to tolerate chelator-induced stress because of its varietal ranges.

In conclusion, three main parameters were found to be important determinants of the cumulative capacity of cannabis: metal concentrations, the presence of the geotextile and the concomitant presence of other metals. The study was chosen to be conducted using mesoplastic dimensions usually observed more frequently than microplastics after the erosion of the geotextile used during agricultural plastics, ensuring that they will not be absorbed by the roots of the plants and, in addition, that the induced changes in the physicochemical properties of the soils will be accelerated. As a consequence of the presence of the geotextile fragments, the metal accumulation capacity was enhanced, due to significant mechanisms, such as the reduction in soil pH, leading to an increase in metal availability and mobility, as well as potential competitive and synergistic phenomena, such as possible adsorption and leaching, complexation, etc. The behavior of the metals studied, i.e., Zn, Cu and Cd, seems to follow a common pattern, but more experiments need to be carried out, on more soil types, so as to obtain critical conclusions for the study of the remediation capacity of heavy-metal-contaminated Mediterranean soils.

4. Conclusions

Industrial hemp seems to be a particularly resilient plant that, despite the stress it underwent during cultivation in soil with geotextile fragments and heavy metals at the maximum concentration allowed by the EU, showed positive results regarding soil remediation. Additionally, the presence of the geotextile positively influenced the plant's ability to accumulate metals in its root tissues, allowing the aerial part to have much lower concentrations, making it suitable for producing ropes and threads. Finally, the simultaneous presence of pollutants seems to have had a beneficial effect as they enhanced the plant's resistance to the toxic soil environment. The results of this preliminary study should be expanded in the future, in a number of soil taxonomy orders, at higher levels of metals, and in different climatic conditions of temperature and humidity, in order to be verified and potentially serve as a valuable tool in selecting conditions for the phytoremediation of contaminated soils. Furthermore, studies should be carried out concerning the possible biochemical mechanisms activated in the plant in response to the stress provided by the soil environment to understand and perhaps predict the effects on the plant's ability to remediate polluted Mediterranean environments.

Author Contributions: Conceptualization, E.E.G. and D.A.; methodology, E.E.G., D.A., S.G.P., E.T. (Eleni Tsaliki), E.T. (Eftihia Tatsi), E.B., P.T., R.V. and J.B.; software, E.E.G., D.A., S.G.P., E.T. (Eleni Tsaliki), E.T. (Eftihia Tatsi), E.B., P.T. and R.V.; validation, E.E.G. and D.A.; formal analysis, E.E.G., D.A., S.G.P., E.T. (Eleni Tsaliki) and E.B.; investigation, E.E.G., D.A., S.G.P., E.T. (Eleni Tsaliki), E.T. (Eftihia Tatsi), E.B., P.T., R.V. and J.B.; resources, E.E.G. and E.T. (Eleni Tsaliki); data curation, E.E.G., D.A. and S.G.P.; writing—original draft preparation, E.E.G., D.A. and S.G.P.; writing—review and editing, E.E.G., D.A. and S.G.P.; visualization, E.E.G., D.A. and S.G.P.; supervision, E.E.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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