horticulturae

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Arsenic Uptake and Distribution in Green Pea Plants Under Arsenite and Arsenate Treatments

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Abstract: Soil arsenic (As) contamination is a global issue affecting regions worldwide. As in the soil is primarily present in inorganic forms, such as arsenite [As(III)] and arsenate [As(V)]. As is a microelement that is toxic to plants grown in As-contaminated soil. The aim of our study was to investigate the effects of increasing concentrations (0, 3, 10, 30, 90, and 270 mg kg^{-1}) of As(III) and As(V) on the As content in green pea (*Pisum sativum* L.) and the distribution of As among different plant parts at four phenophases (the four-node stage, beginning of flowering, green ripening, and mature stage). Another aim was to determine the percentage of total soil As available to plants under different treatments. The results indicate that the developmental stage of the pea and treatment concentration significantly influence the distribution of As among plant organs. However, the differences between the effect of inorganic As forms were less pronounced. The amount of As absorbed by the whole test plant increased with higher treatment concentrations. In the case of As(III)-treatment, As amount in the whole plant increased from 0.170 µg to 7.31 µg (I. Phenophase); from 0.294 µg to 10.1 µg (II. Phenophase); from 0.435 µg to 31.6 µg (III. Phenophase); and from 0.697 µg to 36.1 µg (IV. Phenophase). As a result of As(V)-treatment, the whole plant's As content increased from 0.170 µg to 8.94 µg (I. Phenophase); from 0.294 µg to 17.4 µg (II. Phenophase); from 0.435 µg to 29.7 µg (III. Phenophase); and from 0.697 µg to 58.5 µg (IV. Phenophase). The concentration of As accumulated by the plant also increased over time. The proportion of As absorbed by generative parts was much smaller than that absorbed by vegetative organs. The pea seeds generally accumulated less As (maximum 7%) than the pea pods (in some cases, this reached the 10%). As the total amount of As taken up by the plant increased, the proportion of As reaching the seeds generally decreased (from 5% to 0.3% in the case of As[III]-treatment, and from 5% to 0.1% in the case of As[V]-treatment). At treatment levels where the ability of the stem to retain As increased, a maximum of 1% of the total As absorbed by the plant was found in the seeds. Depending on the treatment, 3.82–5.69% [As(V)-treatments] and 3.9–6.07% [As(III)-treatments] of the total soil As were available to the plants. The difference in the ratio of the total As content to the soluble As content was more evident at higher treatment levels (≥30 mg kg^{-1}). This value was typically lower for the As(V)-treatments.

Keywords: arsenite; arsenate; soil; *Pisum sativum* L.; As accumulation; As distribution

Citation: Várallyay, S.; Bódi, É.; Balla Kovács, A.; Soós, Á.; Mukarram, S.A.; Kovács, B. Arsenic Uptake and Distribution in Green Pea Plants Under Arsenite and Arsenate Treatments. *Horticulturae* **2024**, *10*, 1127. https://doi.org/10.3390/horticulturae10111127

Academic Editor: Georgios Koubouris

Received: 13 August 2024
Revised: 29 September 2024
Accepted: 22 October 2024
Published: 23 October 2024

1. Introduction

Soil and groundwater contamination are severe environmental issues. As (As) is a contaminating element that causes global problems [1,2]. Soil and groundwater As

contamination exist in several regions, including the USA, Argentina, Austria, Bangladesh, Chile, China, India, and parts of Hungary [2–5].

As contamination sources in soil and groundwater can be both natural and anthropogenic [2]. A significant portion of environmental As contamination is from human activities, with natural origin contributing a smaller proportion [6].

The As content in arable soil primarily depends on the parent rock [7], resulting in significant regional differences in the natural As content [6]. Uncontaminated soil typically contains 1–40 mg kg^{-1} of As [8]. Lower concentrations are typical for sandy and granitic soil, whereas higher values are found in alluvial and high organic matter soil [6].

In soil [9–12] and groundwater, As is mainly present in inorganic forms, which are much more toxic than organic forms [2]. In well-aerated soil under oxidative conditions, arsenate [As(V)] is common, whereas in anaerobic, waterlogged, and compacted soil, arsenite [As(III)] is the prevalent inorganic As form [2]. In terms of toxicity, As(III) is more toxic than As(V) [13].

Soluble As content in soil better characterizes the biologically utilizable and mobilizable As contents than the total As content [14]. The amount of As available to plants in soil is determined by several environmental factors (pH, Eh, organic matter content, presence of other ions, etc.) [15–21]. Only a small portion of the total soil As is available to plants and is strongly bound to soil constituents [22]. Field studies showed that, with increasing soil As concentration, the As concentration in the sunflower test plant also increased. As content in rice and other plant parts presented the following order based on the As content in different plant parts: root > stem > leaf > grain > husk [23]. The amount of As in reproductive tissues does not increase significantly, even when the phytotoxic effect of As reduces plant growth by 50%. The amount of As absorbed by plants depends also on the Fe and Mn content in soil [21]. The amount of As absorbed by plants depends not only on the total soil As content, but also on the form in which As is present in the growing medium [24]. They found the following order of As uptake based on the different As forms: organic As > As(V) > As (III).

As is a non-essential and toxic microelement in plants [25–27]. Once inside a plant, it can inhibit various metabolic processes [28]. However, plants can survive abiotic stresses because of their defense mechanisms up to certain concentration levels. The As content in plants varies between 0.01 and 5 μg g^{-1} dry weight, depending on the environmental As content [29]. For plants grown in uncontaminated soil, this value ranges between 0.5 and 80 μg kg^{-1} [30]. A higher As content is primarily observed in vegetables and As-tolerant plants. Different plant species exhibit varying As tolerance levels. Potatoes, cabbage, tomatoes, carrots, tobacco, rye, Sudan grass, and grapes can tolerate high As concentrations, whereas maize, beetroot, and strawberries are moderately tolerant. Low tolerance is a characteristic of onions, cucumbers, and legumes [31–33].

The accumulation of contaminant elements in soil due to natural processes and anthropogenic activities generally remains stable, indicating that such contamination is not only a current issue, but also a future concern [34,35].

The aim of this study was to investigate the effects of As(III) and As(V) in a greenhouse experiment. Green peas (*Pisum sativum* L.) were chosen as the test plant. Pea is the second most widely cultivated legume in the world. Furthermore, many pea-producing countries are affected by soil As contamination [36]. Our study presents the effects of As(III) and As(V) treatments on the As content of green peas (*Pisum sativum* L.) and the distribution of As among different plant parts (the root, stem, leaf, pod, and seed) during four phenophases (the four-node stage, beginning of flowering, green ripening, and mature stage).

In the soil tests, our aim was to determine what percentage of the total As content in the soil is available to plants (soluble As content) in the cases of As (III) and As(V) treatments.

2. Materials and Methods

Greenhouse Experiment

The experiment was conducted in calcareous chernozem soil from the Látókép Experimental Station of the Faculty of Agricultural and Food Sciences and Environmental Management at the University of Debrecen. The soil characteristics used in the experiment are described in Table 1 [37].

Table 1. Characteristics of the calcareous chernozem soil used in the experiment.

No.	Experiment	Values
1.	Depth	0–0.3 m
2.	pH (KCl)	5.71
3.	pH (H_2O)	6.58
4.	Soil texture category	Loamy clay
5.	Total water-soluble salt	0.015%
6.	$CaCO_3$	0.202%
7.	Humus	3.54%
8.	KCl-soluble NO_3-N+NO_2-N	8.04
9.	AL-soluble P_2O_5	199 mg kg^{-1}
10.	AL-soluble K_2O	451 mg kg^{-1}
11.	AL-soluble Na	332 mg kg^{-1}
12.	KCl-soluble Mg	176 mg kg^{-1}
13.	KCl-soluble $SO_4{}^{2-}$-S	6.04 mg kg^{-1}
14.	KCl-EDTA-soluble Cu	5.79 mg kg^{-1}
15.	KCl-EDTA-soluble Zn	7.9 mg kg^{-1}
16.	KCl-EDTA-soluble Mn	262 mg kg^{-1}

Air-dried (11 kg) sieved soil (1 × 1 cm mesh) was measured into each pot.

Fertilization was provided as follows: nitrogen as NH_4NO_3 (0.568 g pot^{-1}), phosphorus as KH_2PO_4 (0.229 g pot^{-1}), potassium as KH_2PO_4 (0.079 g pot^{-1}), and K_2SO_4 (0.148 g pot^{-1}) were added to 100 cm^3 of distilled water solution per pot. (All the materials were purchased by different suppliers from different part of the world including Schar lab, Barcelona, Spain, Biolab and VWR international Ltd., Radnor, PA, USA).

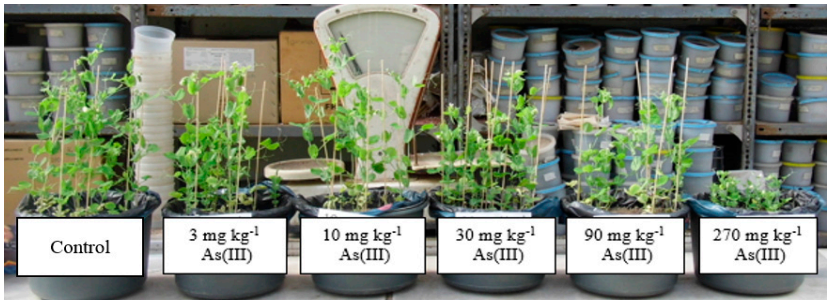
As was added to the soil in the form of potassium dihydrogen arsenate (KH_2AsO_4) and sodium arsenite ($NaAsO_2$), dissolved in ion-exchanged water (100 cm^3 pot^{-1}). Treatments of 0 (control), 3, 10, 30, 90, and 270 mg kg^{-1} were applied to each As form in 3 replicates. As was added to the soil 1 week before peas planting.

We planted 25 pea seeds per pot, and this was thinned to 16 plants per pot after germination. The experiment was arranged in a randomized block design. Soil moisture was maintained at 60% of the maximum field capacity. Water loss due to evaporation and transpiration was compensated daily based on weight replenishment.

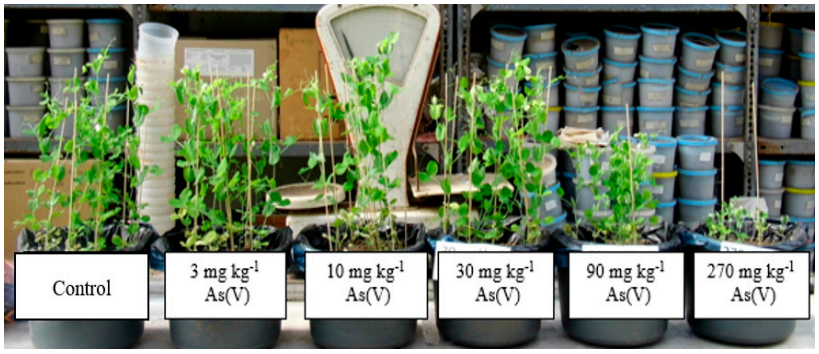
The greenhouse experiment was terminated at four Phenophase (four-node stage, beginning of flowering, green ripening, and mature stage) (Figure 1).

The differences in the toxicity of trivalent and pentavalent arsenic were pronounced in the dry mass, as shown in Figure 1. The result of the dry mass has been published previously [38].

The key operations' dates are listed in Table 2.



(**A**)



(**B**)

Figure 1. (**A**,**B**) effects of increasing concentrations (0, 3, 10, 30, 90, and 270 mg kg^{-1}) of As(III) and As(V) treatments on pea plant development at full ripeness. (**A**) Effects of increasing concentrations (0, 3, 10, 30, 90, and 270 mg kg^{-1}) of As(III) treatments on pea plant development at the mature stage. (**B**) Effects of increasing concentrations (0, 3, 10, 30, 90, and 270 mg kg^{-1}) of As(V) treatments on pea plant development at the mature stage. The captions in the pictures show the treatment concentrations. As(III) means arsenite treatment; As(V) means arsenate treatment.

Table 2. Dates of major operations in the greenhouse experiment.

No.	Process Timeline	Dates of Experiments
1.	Soil mixing	5 April
2.	Soil sampling	12 April
3.	Pea sowing	12 April
4.	I. Phenophase (four-node stage)	11 May
5.	II. Phenophase (beginning of flowering)	24 May
6.	III. Phenophase (green ripening)	6 June
7.	IV. Phenophase (mature stage)	13 June

During each Phenophase, four plants per pot were carefully removed to keep the roots intact. Soil particles were washed off from the roots with tap water and distilled water. The plants were separated into roots, stems, leaves, and pods (III. and IV. Phenophases), and the seeds (IV. Phenophase), and then dried in a Memmert UF 75 drying oven at 65 °C to a constant weight.

3. Preparation of Soil and Plant Samples

3.1. Preparation of Soil Samples

Soil sampling was performed on the same day as pea sowing, one week after soil mixing. Three sub-samples were collected from each pot.

3.2. Soluble As Content in Soil

After thoroughly homogenizing and drying the soil samples, we determined the soil soluble As content using the method developed by Lakanen–Erviö [39]. From the soil sample, 15 g was measured into a scintillation vial, and 15 cm^3 of diluted extractant (0.5 M ammonium acetate + 0.5 M acetic acid + 0.02 M H_4EDTA, pH = 4.65) was added. The vials were shaken for 60 min. The samples were filtered using Munktell Ahlstrom filter paper.

3.3. Total As Content in Soil

To determine the total As content, 1 g of the prepared (dried, homogenized) soil sample was measured in heat-resistant digestion tubes, and 5 cm^3 concentrated HNO_3 was added. The next day, the tubes were placed in an electric block digester (LABOR MIM OE-718/A). The samples were maintained at 60 °C for 30 min, 5 cm^3 30% H_2O_2 was added, and the main digestion was carried out at 120 °C for 270 min. After cooling to room temperature, the digests were diluted to 50 cm^3 with twice-distilled water and filtered through Filtrak 388 filter paper [40].

3.4. Preparation of Plant Samples

Plant samples were homogenized using a mortar and pestle after drying to a constant weight. The wet digestion method with HNO_3-H_2O_2 developed by Kovács et al. (1996) [41] was used. A total of 0.1 g (±0.001 g) of the prepared samples was measured in heat-resistant test tubes. A total of 1 cm^3 HNO_3 was added, and the mixture was left overnight. The next day, the test tubes were placed in an electric block digester (LABOR MIM OE-718/A) at 60 °C for 30 min. Then, 0.3 cm^3 30% H_2O_2 was added, and the main digestion was carried out at 120 °C for 90 min. After cooling to room temperature, the digests were diluted to 10 cm^3 with ion-exchanged water (conductivity: 18.2 MΩ cm) and filtered through Filtrak 388 filter paper.

3.5. Elemental Analysis

To determine the As content of the soil and plant samples, we used a Thermo Scientific X-Series 2 quadrupole ICP-MS and an iCAP 6300 Dual ICP-OES (Thermo Fisher Scientific, Waltham, MA, USA). The ICP-OES and ICP-MS were controlled by iTEVA 2.8.0.97 and Thermo Plasma Lab 2.5.10.319 software. The measurement and setup parameters were the same as those used by Soós et al. [42]. ICP-OES parameters were the following: forward power of 1350 W, plasma gas flow rate of 12.0 L min^{-1}, nebulizer gas flow rate of 1.0 L min^{-1}, auxiliary gas flow rate of 1.0 L min^{-1}, sample uptake speed of 50 rpm, and plasma view axial.

ICP-MS parameters were as follows: forward power of 1400 W, plasma gas flow rate of 14.0 L min^{-1}, nebulizer gas flow rate of 0.86 L min^{-1}, auxiliary gas flow rate of 0.88 L min^{-1}, sample uptake speed of 20 rpm, dwell time of 100 ms, sweep of 9, and main run of 3. Collision cell gas (H_2-He in 7:93%) was applied (6.0 mL min^{-1} flow rate). For the quantification of the As content, digested samples were diluted five times to decrease the acid content of the solution. Rh (40 μg L^{-1}) was used as an internal standard. The experiment included the digestion and analysis of the reference soil (Wepal ISE 2010-3-1 calcareous clay soil, reference median value: 18.91 mg kg^{-1}) and plant (Wepal IPE 2007-1-2 green peas sample, reference median value: 15.2 μg kg^{-1}) samples. The measured values (18.85 mg kg^{-1} in the case of the soil, 15.0 μg kg^{-1} in the case of the plant) were within the margin of error in both cases.

3.6. Statistical Methods

Statistical analyses were performed using SPSS 22.0. One-way ANOVA and Duncan's tests were used to examine the relationships between parameters and factors. Differences were considered significant at $p \leq 0.5$.

4. Results

4.1. Soil Examination Results

The amount of As available to plants is primarily determined by the soluble As content rather than the total As content. The results are summarized in Table 3.

Table 3. Total and soluble As content in the calcareous chernozem soil used in the experiment (mg kg^{-1}) and their ratios based on the applied treatments (0, 1, 3, 10, 30, 90, and 270 mg kg^{-1} As) (mean ± standard deviation).

As Treatment (mg kg^{-1})		"Total" As Content (mg kg^{-1}) (A)	"Soluble" As Content (mg kg^{-1}) (B)	B/A
As(III)	0	2.07 ± 0.04 [a]	0.799 ± 0.064 [a]	0.386
	1	3.23 ± 0.17 [a]	1.61 ± 0.12 [ab]	0.497
	3	5.20 ± 0.28 [a]	2.54 ± 0.78 [ab]	0.488
	10	12.4 ± 1.7 [b]	4.84 ± 0.12 [b]	0.390
	30	31.9 ± 1.8 [c]	19.3 ± 1.6 [c]	0.607
	90	93.4 ± 1.2 [d]	53.3 ± 3.2 [d]	0.570
	270	273 ± 6 [e]	162 ± 10 [e]	0.593
As(V)	0	2.07 ± 0.04 [a]	0.799 ± 0.064 [a]	0.386
	1	3.20 ± 0.60 [a]	1.57 ± 0.20 [ab]	0.490
	3	5.26 ± 0.25 [a]	2.53 ± 0.37 [ab]	0.481
	10	11.6 ± 0.1 [b]	4.42 ± 0.18 [ab]	0.382
	30	32.1 ± 0.5 [c]	15.7 ± 1.1 [b]	0.488
	90	92.0 ± 4.3 [d]	39.1 ± 2.6 [c]	0.425
	270	269 ± 4 [e]	153 ± 17 [d]	0.569

In the case of each As form, there was a significant difference between treatments marked with [a], [b], [c], [d], and [e] at the 0.5 significance level.

The control soil contained As (2.07 ± 0.04 mg kg^{-1}). The As(III) and As(V) treatments increased both the "total" and "soluble" As content in the soil. In the control soil, 38.6% of the As content was available to the plants. In the As(III) treatments, this value was in the range of 39–60.7%, and in the As(V) treatments, it was in the range of 38.2–56.9%. For the 30–270 mg kg^{-1} As(III) doses and the 270 mg kg^{-1} As(V) dose, more than half of the "total" As content in the soil was available to plants.

4.2. Effects of As(III) and As(V) Treatments on the As Content of Green Peas Grown in Pots

The results in Tables 4 and 5 indicate that, in the I-II Phenophases, the total amount of As absorbed by the plants increases with the concentration of treatments.

The data in Tables 4 and 5 also indicate that the amount of As absorbed by plants is greatly influenced by the amount of As in the soil and the developmental stage of the plant.

In I. Phenophase, approximately half of the As absorbed by the control plant was present in the leaf, with the rest evenly distributed between the stem and root. In contrast, for plants grown in As(III)- and As(V)-treated soil, the largest amount of As was found in the roots. Comparing the amount of As absorbed by the leaf and stem, we observed that for the 3–90 mg kg^{-1} As(III) and As(V) treatments, the amount of As in the leaf greatly exceeded that in the stem. For the 270 mg kg^{-1} As(V) dose, however, the amounts of As in the leaves and stems were approximately equal, whereas for the As(III) treatment, the stem contained more As than the leaf.

Table 4. Amount of As absorbed by green pead grown in pots at increasing concentrations of As(III) treatments (0, 3, 10, 30, 90, and 270 mg kg^{-1}) (mean ± standard deviation).

As(III) Treatment (mg kg^{-1})	Amount of As Absorbed by Green Pea Vegetative Organs (µg)							
	I. Phenophase (Four-Node Stage)				II. Phenophase (Beginning of Flowering)			
	Leaf	Stem	Root	Whole Plant	Leaf	Stem	Root	Whole Plant
0	0.0854 ± 0.001 ^{a}	0.0391 ± 0.0007 ^{a}	0.0459 ± 0.0009 ^{a}	0.170	0.126 ± 0.002 ^{a}	0.0867 ± 0.0005 ^{a}	0.0809 ± 0.0022 ^{a}	0.294
3	0.0791 ± 0.0004 ^{a}	0.0422 ± 0.0002 ^{a}	0.119 ± 0.003 ^{a}	0.240	0.116 ± 0.001 ^{a}	0.1046 ± 0.0005 ^{ab}	0.279 ± 0.004 ^{b}	0.500
10	0.130 ± 0.001 ^{b}	0.057 ± 0.001 ^{a}	0.205 ± 0.005 ^{a}	0.392	0.286 ± 0.015 ^{a}	0.245 ± 0.005 ^{b}	0.319 ± 0.012 ^{b}	0.850
30	0.542 ± 0.005 ^{b}	0.228 ± 0.001 ^{b}	1.28 ± 0.03 ^{b}	2.05	0.859 ± 0.006 ^{b}	0.637 ± 0.003 ^{b}	2.90 ± 0.33 ^{c}	4.40
90	0.874 ± 0.008 ^{b}	0.330 ± 0.000 ^{b}	4.01 ± 0.03 ^{b}	5.21	0.989 ± 0.016 ^{b}	1.588 ± 0.048 ^{c}	6.12 ± 0.11 ^{c}	8.70
270	0.269 ± 0.013 ^{b}	0.882 ± 0.015 ^{b}	6.16 ± 0.12 ^{b}	7.31	0.623 ± 0.046 ^{b}	1.49 ± 0.02 ^{c}	8.00 ± 0.20 ^{c}	10.1

In the case of the same plant part, there is a significant difference between treatments marked with ^{a}, ^{b}, and ^{c} at the 0.5 significance level. Values represent the percentage of total As absorbed by a specific plant part.

Table 5. Amount of As absorbed by green peas grown in pots at increasing concentrations of As(V) treatments (0, 3, 10, 30, 90, and 270 mg kg^{-1}) (mean ± standard deviation).

As(V) Treatment (mg kg^{-1})	Amount of As Absorbed by Green Pea Vegetative Organs (µg)							
	I. Phenophase (Four-Node Stage)				II. Phenophase (Beginning of Flowering)			
	Leaf	Stem	Root	Whole Plant	Leaf	Stem	Root	Whole Plant
0	0.0854 ± 0.001 ^{a}	0.0391 ± 0.0007 ^{a}	0.0459 ± 0.0009 ^{a}	0.170	0.126 ± 0.002 ^{a}	0.0867 ± 0.0005 ^{a}	0.0809 ± 0.0022 ^{a}	0.294
3	0.129 ± 0.001 ^{ab}	0.0840 ± 0.0030 ^{a}	0.285 ± 0.006 ^{b}	0.498	0.165 ± 0.027 ^{a}	0.168 ± 0.007 ^{b}	0.322 ± 0.01 ^{b*}	0.655
10	0.392 ± 0.005 ^{b}	0.161 ± 0.001 ^{b}	0.464 ± 0.016 ^{b}	1.02	0.880 ± 0.006 ^{a}	0.752 ± 0.027 ^{b}	0.761 ± 0.014 ^{b}	2.39
30	0.363 ± 0.004 ^{b}	0.208 ± 0.007 ^{b}	1.30 ± 0.09 ^{c}	1.87	0.920 ± 0.020 ^{a}	0.883 ± 0.006 ^{bc}	2.80 ± 0.02 ^{c}	4.61
90	1.08 ± 0.02 ^{c}	0.540 ± 0.001 ^{b}	7.72 ± 0.07 ^{d}	9.34	1.22 ± 0.07 ^{b}	1.07 ± 0.02 ^{c}	9.86 ± 0.03 ^{d}	12.2
270	0.234 ± 0.003 ^{b}	0.402 ± 0.005 ^{b}	8.30 ± 0.20 ^{d}	8.94	0.409 ± 0.001 ^{a}	0.617 ± 0.165 ^{b}	16.3 ± 0.1 ^{e}	17.4

In the case of the same plant part, there is a significant difference between treatments marked with ^{a}, ^{b}, ^{c}, ^{d}, and ^{e} at the 0.5 significance level. Values represent the percentage of total As absorbed by a specific plant part. As treatment: * $p < 0.05$.

In II. Phenophase, the control plant showed similar results to I. Phenophase, with approximately half of the As absorbed accumulating in the leaf, and the rest evenly distributed between the stem and root. The data from Tables 4 and 5 also highlight that most of the As absorbed from the soil is present in the roots, and the proportions of As in the stems and leaves are approximately equal for both treatment forms. The 10 mg kg^{-1} treatment was an exception, where the amount of As absorbed by the pea plant was approximately equally distributed among the vegetative parts.

In the green-ripening Phenophase (III Phenophase), the amount of As absorbed by the pea plants based on treatments is summarized in Tables 6 and 7.

In the green-ripening Phenophase (III. Phenophase), the pod As content relative to the total amount of As absorbed by the plant was very low for both treatment forms. The pod contained a maximum of 1% of the total As absorbed by the plant for the As(V) treatments, but this value was not reached in the As (III) treatments.

When examining the As concentration in the vegetative parts, we found that the proportion of As retained by the root increased with As(V) doses above 3 mg kg^{-1}. At the highest (270 mg kg^{-1}) As(V) dose (270 mg kg^{-1}), 94% of the total As absorbed by the test plant was present in the root. However, it is important to note that for the 0–10 mg kg^{-1} As(V) treatments, the highest proportion of As was not in the root, but in the leaf. We also observed that the proportion of As in the leaf exceeded that in the stem for the 0–90 mg kg^{-1} As(V) treatments, but in the highest treatment, the As content in the leaf and stem was equalized.

Table 6. Amount of As absorbed by green pea plants in the green-ripening Phenophase at increasing concentrations of As(III) treatments (0, 3, 10, 30, 90, and 270 mg kg^{-1}) (mean ± standard deviation).

As(III) Treatment (mg kg^{-1})	Amount of As Absorbed by Green Pea (µg)				
	Pod	Leaf	Stem	Root	Whole Plant
0	<LOD [a]	0.160 ± 0.001 [a]	0.134 ± 0.004 [a]	0.141 ± 0.001 [a]	0.435
3	<LOD [a]	0.236 ± 0.003 [a]	0.128 ± 0.003 [a]	0.562 ± 0.033 [a]	0.926
10	<LOD [a]	0.513 ± 0.009 [a]	0.315 ± 0.024 [a]	1.74 ± 0.02 [b]	2.58
30	0.0124 ± 0.0012 [b]	1.15 ± 0.06 [b]	1.46 ± 0.03 [b]	6.24 ± 0.08 [c]	8.89
90	0.0200 ± 0.0001 [b]	1.61 ± 0.02 [b]	3.00 ± 0.10 [b]	14.2 ± 0.8 [d]	19.0
270	0.0900 ± 0.0010 [b]	0.902 ± 0.038 [b]	1.80 ± 0.01 [b]	28.5 ± 0.3 [e]	31.6

In the case of the same plant part, there is a significant difference between treatments marked with [a], [b], [c], [d], and [e] at the 0.5 significance level. Values represent the percentage of total As absorbed by a specific plant part. LOD means below the limit of detection (1.9 µg kg^{-1}).

Table 7. Amount of As absorbed by green pea plants in the green-ripening Phenophase at increasing concentrations of As(V) treatments (0, 3, 10, 30, 90, and 270 mg kg^{-1}) (mean ± standard deviation).

As(V) Treatment (mg kg^{-1}) Increasing Concentrations	Amount of As Absorbed by Green Pea (µg)				
	Pod	Leaf	Stem	Root	Whole Plant
0	<LOD [a]	0.160 ± 0.001 [a]	0.134 ± 0.004 [a]	0.141 ± 0.001 [a]	0.435
3	<LOD [a]	0.677 ± 0.005 [a]	0.609 ± 0.014 [a]	0.461 ± 0.003 [a]	1.75
10	<LOD [a]	1.61 ± 0.02 [b]	0.946 ± 0.011 [ab]	1.27 ± 0.01 [b]	3.83
30	0.0629 ± 0.0073 [b]	1.61 ± 0.06 [b]	1.06 ± 0.01 [b]	5.06 ± 0.23 [b]	7.79
90	0.0364 ± 0.0012 [b]	1.55 ± 0.02 [b]	1.25 ± 0.02 [b]	22.9 ± 0.2 [d]	25.7
270	0.17 ± 0.004 [c]	0.751 ± 0.063 [a]	0.762 ± 0.012 [a]	28.0 ± 0.2 [d]	29.7

In the case of the same plant part, there is a significant difference between treatments marked with [a], [b], [c], and [d] at the 0.5 significance level. Values represent the percentage of total As absorbed by a specific plant part. <LOD means that it is under the limit of detection (1.9 µg kg^{-1}).

For the As (III) treatments, the ability of the root to retain As increased with the treatments, and we observed that, in most cases, the highest proportion of absorbed As was in the root, with the proportion in the leaf exceeding that in the stem, only for the 0–10 mg kg^{-1} treatments.

The results also indicate that increasing the soil As content significantly increases the total amount of As absorbed by the plant for both treatment forms, as well as in the full ripeness Phenophase (IV. Phenophase) (Tables 8 and 9).

Table 8. Amount of As absorbed by green pea plants in the mature stage Phenophase at increasing concentrations of As(III) treatments (0, 3, 10, 30, 90, and 270 mg kg^{-1}) (mean ± standard deviation).

As(III) Treatment (mg kg^{-1})	Amount of As Absorbed by Green Pea (µg)					
	Seed	Pod	Leaf	Stem	Root	Whole Plant
0	0.0365 ± 0.0019 [a]	0.0665 ± 0.0013 [a]	0.180 ± 0.003 [a]	0.153 ± 0.003 [a]	0.261 ± 0.001 [a]	0.697
3	0.0873 ± 0.0026 [a]	0.203 ± 0.011 [b]	1.02 ± 0.02 [b]	0.608 ± 0.058 [ab]	0.702 ± 0.002 [a]	2.62
10	0.0923 ± 0.0007 [a]	0.192 ± 0.003 [b]	1.65 ± 0.02 [b]	0.912 ± 0.011 [b]	3.02 ± 0.06 [b]	5.87
30	0.0733 ± 0.0008 [a]	0.164 ± 0.008 [b]	1.74 ± 0.01 [b]	2.11 ± 0.01 [c]	10.1 ± 0.2 [c]	14.1
90	0.0805 ± 0.0022 [a]	0.123 ± 0.001 [b]	3.68 ± 0.15 [c]	4.57 ± 0.25 [d]	20.6 ± 0.5 [d]	29.1
270	0.1306 ± 0.0032 [b]	0.437 ± 0.007 [c]	1.71 ± 0.04 [b]	4.42 ± 0.04 [d]	29.4 ± 0.12 [d]	36.1

In the case of the same plant part, there is a significant difference between treatments marked with [a], [b], [c] and [d] at the 0.5 significance level. Values represent the percentage of total As absorbed by a specific plant part.

Table 9. Amount of As absorbed by green pea plants in the full ripeness Phenophase at increasing concentrations of As(V) treatments (0, 3, 10, 30, 90, and 270 mg kg^{-1}) (n = 3 ± s.e.).

As(V) Treatment (mg kg^{-1})	Amount of As Absorbed by Green Pea (µg)					
	Seed	Pod	Leaf	Stem	Root	Whole Plant
0	0.036 ± 0.002 [a]	0.0664 ± 0.0013 [a]	0.180 ± 0.003 [a]	0.153 ± 0.003 [a]	0.261 ± 0.001 [a]	0.696
3	0.170 ± 0.001 [b]	0.162 ± 0.002 [b]	0.845 ± 0.002 [b]	0.786 ± 0.011 [a]	0.623 ± 0.011 [a]	2.59
10	0.182 ± 0.008 [b]	0.259 ± 0.003 [b]	2.64 ± 0.01 [c]	1.53 ± 0.01 [b]	1.41 ± 0.01 [b]	6.02
30	0.140 ± 0.01 [b]	0.198 ± 0.001 [b]	2.36 ± 0.01 [c]	1.98 ± 0.01 [b]	7.82 ± 0.07 [c]	12.5
90	0.180 ± 0.001 [b]	0.408 ± 0.007 [b]	2.90 ± 0.01 [c]	5.19 ± 0.04 [c]	30.42 ± 0.09 [d]	39.1
270	0.070 ± 0.001 [b]	0.79 ± 0.017 [c]	5.63 ± 0.17 [d]	10.8 ± 0.2 [d]	41.23 ± 0.21 [e]	58.5

In the case of the same plant part, there is no significant difference between treatments marked with the same letter ($p \leq 0.5$). Values represent the percentage of total As absorbed by a specific plant part.

The data from Tables 8 and 9 indicate that, for both treatment types, the smallest amount of As is present in the generative parts. Additionally, the amount of As accumulated in the generative parts relative to the total As absorbed by the plant decreased with increasing treatment concentrations in most cases. It is also important to highlight that the proportion of As absorbed by the pods exceeded that in the seeds for both treatment forms in almost every case.

When examining the amount of As absorbed by vegetative plant parts, we found that the proportion of As retained by the roots increased with As (III) doses above 3 mg kg^{-1}. In most cases, the majority of the absorbed As accumulated in the root, with the proportion of As in the leaf exceeding that in the root only for the 3 mg kg^{-1} As (III) and 3–10 mg kg^{-1} As(V) doses.

The data also indicate that, for the lower-concentration As (III) treatments (0–10 mg kg^{-1}), the proportion of As absorbed by the leaf exceeds that in the stem. However, for the 30–270 mg kg^{-1} treatments, the opposite was observed, with the roots and stems retaining more As. For the As (V)-treatments, this was only observed for the 90–270 mg kg^{-1} doses.

5. Discussions

5.1. Soil Examination Results

The results indicate that only a portion of the total As content in the soil is available to the plants. This is likely due to the good humus content of the soil used in the experiment (Table 1), which can bind some of the As in the soil, thus inhibiting the mobility of As in the soil–plant system [43,44]. Additionally, As can bind to the surfaces of iron, magnesium, aluminum, manganese oxides, and hydroxides present in soil, further inhibiting its mobility. This type of binding can occur for both arsenite and arsenate, although arsenates are typically adsorbed in large amounts [21]. This likely contributed to the lower ratio of soluble As content to total As content observed for the As(V) treatments, especially at higher (≥30 mg kg^{-1}) treatment levels.

The pH of the calcareous chernozem soil used in the experiment was near neutral (6.58) (Table 1). Under nearly neutral conditions, metals are less likely to dissolve, and their compounds are stable [45], which may have also contributed to the lower soluble As concentration compared to the total As content.

These findings are similar to those of [22,46–48], who concluded that only a small portion of the total As content in the soil is available to plants. These results also support the assertion that As mobility is proportional to the amount of As introduced into the soil [49].

5.2. Plant Examination Results

In the greenhouse experiment, we found that the developmental stage of the plants and the treatment concentration significantly influenced the distribution of As among

plant organs. However, the differences between the effects of inorganic As forms were less pronounced.

For both treatment forms, we found that the increasing concentration treatments increased As accumulation in the test plant, and the amount of As absorbed by each plant part increased continuously during the development of the peas, as did the total As concentration absorbed by the plant. This is consistent with the findings of other studies that higher As treatment concentrations increase the As content in various plant parts [50–54].

Generally, the As concentration that accumulated in the roots increased with higher treatment concentrations for most phenophases. However, it is important to note that, for lower treatment concentrations ($\leq$10 mg kg^{-1}), the highest proportion of absorbed As was often present in the leaves rather than the roots. This is like the findings of [24], who observed that, for soil with a low As content, the As concentration in the leaves of radishes exceeded that in the roots. The translocation of arsenic is not very efficient in most plant species, with the exception of hyperaccumulator plants. Most of the arsenic accumulates in the root [28]. One possible explanation for this is that As forms a complex with phytochelatin and accumulates in the vacuole, resulting in a decrease in its transport toward the xylem [26,28]. The synthesis of phytochelatins, polypeptides involved in the exclusion, sequestration, and binding of toxic metal ions, starts first in the root, as this is the part of the plant where arsenic first appears during plant uptake and where, according to the experimental results, it predominantly accumulates. In the case of arsenic treatment-induced stress processes, it can be interpreted as part of the plant's detoxification mechanism that arsenic accumulates predominantly in the root. This defense mechanism allows them to survive this kind of abiotic stress [28]. Raab et al. [55] also suggest that plants are protected from poisoning by storage in the vacuoles.

In the early stages of plant development (I. phenophase), the proportion of As in the leaves exceeded that in the stems, in most cases. As time progressed, the As content in the leaf and stem became approximately equal, and the As-retention capability of the stem increased. This can also be interpreted as part of the plant's detoxification mechanism.

The results indicate that generative organs receive less As than vegetative organs. Additionally, the proportion of As in the pod generally exceeded that in the seed. The results also show that, at treatment levels where the ability of the stem to retain As increases relative to the leaf, a maximum of 1% of the total As absorbed by the plant reaches the pea seed, which is an important finding, from a human nutrition perspective. This supports the assertion that As is difficult to move within the plant, and only a small portion reaches the generative organs [23,50,56–58].

6. Conclusions

Arsenic is a toxic element for plants. In this study, we also investigated the effect of As(III) and As(V) treatments on the arsenic content of green peas. The critical arsenic concentration to the arsenic content of the crop is highly dependent on the soil type. Our results are valid for calcareous chernozem soil. The concentrations used range from uncontaminated to heavily contaminated soil (270 mg kg^{-1} provocative concentration). The study demonstrated that the distribution of As among plant organs was primarily determined by the treatment concentration and the developmental stage of the plant, with less pronounced differences between the effects of the As forms. Increasing the soil As content increased the total amount of As absorbed by the test plant for both treatment forms.

Overall, a much smaller proportion of As reached the generative parts of the pea compared to the vegetative parts.

The total and soluble As contents of the soil were also investigated. The results of the experiment show that only a small portion of the total As content in the soil is available to the plants. The amount of available As ("soluble" As content) generally increased with the total As content in the soil. Differences in the ratio of the total As content to the soluble

As content were more evident at higher treatment levels (≥30 mg kg^{-1}). For the As(V) treatments, this ratio was typically lower.

To avoid excessive As in peas, it is advisable to carry out preventive soil tests before planting. On the basis of the soil test results, it can be concluded that the excessive amount of As in peas can be avoided.

Author Contributions: Conceptualization: A.B.K. and B.K.; methodology, A.B.K., S.V., S.A.M. and B.K.; software, S.A.M.; validation, Á.S.; formal analysis, S.V. and S.A.M.; investigation, S.V., Á.S. and É.B.; resources, B.K; data curation, S.V., Á.S. and B.K.; writing—original draft preparation, S.V.; writing—review and editing, S.A.M., Á.S. and B.K.; visualization, S.A.M. and S.V.; supervision, B.K.; project administration, B.K.; funding acquisition, B.K. All authors have read and agreed to the published version of the manuscript.

Funding: Project No. TKP2021-NKTA-32 was implemented with support from the National Research, Development, and Innovation Fund of Hungary, financed under the TKP2021-NKTA funding scheme, and supported by the University of Debrecen Program for Scientific Publication.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. (The data are not publicly available due to privacy or ethical restrictions given by the university.)

Acknowledgments: We are thankful to all authors for their contribution and the University of Debrecen for providing the wonderful opportunity to conduct our research.

Conflicts of Interest: The authors declare that there are no conflicts of interest regarding the publication of this article.

References

1. Liao, X.Y.; Chen, T.B.; Lei, M.; Huang, Z.C.; Xiao, X.Y.; An, Z.Z. Root distributions and elemental accumulations of Chinese brake (*Pteris vittata* L.) from As-contaminated soils. *Plant Soil* **2004**, *261*, 109–116. [CrossRef]
2. Mandal, K.B.; Suzuki, T.K. Arsenic around the world: A review. *Talanta* **2002**, *58*, 201–235. [CrossRef] [PubMed]
3. Mukherjee, A.B.; Bhattacharya, P. Arsenic in the groundwater in the Bengal Delta Plain: Slow poisoning in Bangladesh. *Environ. Res.* **2001**, *9*, 189–220. [CrossRef]
4. Smedley, P.L.; Kinniburgh, D.G. A review of the source, behaviour and distribution of arsenic in natural waters. *Appl. Geochem.* **2002**, *17*, 517–568. [CrossRef]
5. Rowland, H.A.L.; Omoregie, E.O.; Millot, R.; Jimenez, C.; Mertens, J.; Baciu, C.; Hug, S.J.; Berg, M. Geochemistry and arsenic behaviour in groundwater resources of the Pannonian Basin (Hungary and Romania). *Appl. Geochem.* **2011**, *26*, 1–17. [CrossRef]
6. Nriagu, J.O.P.; Bhattacharya, P.; Mukherjee, A.B.; Bundschuh, J.; Zevenhoven, R.; Loeppert, R.H. Arsenic in soil and groundwater: An overview. *Trace Met. Other Contam. Environ.* **2007**, *9*, 3–60. [CrossRef]
7. Ramos-Miras, J.J.; Díaz-Férnandez, P.; SanJosé-Wery, A.; Rodríguez-Martin, J.A.; Roca, N.; Bech, J.; Roca-Perez, L.; Boluda, R.; Gil, C. Influence of parent material and soil use on arsenic forms in soils: A case study in the Amblés Valley (Castilla-León, Spain). *J. Geochem. Explor.* **2014**, *147*, 260–267. [CrossRef]
8. Yang, X.; Liu, L.; Qiu, W.G. Remediation of As-contaminated soils using citrate extraction coupled with electrochemical removal. *Sci. Total Environ.* **2022**, *817*, 153042. [CrossRef]
9. Takamatsu, T.; Aoki, H.; Yoshida, T. Determination of arsenate, arsenite, monomethylarsonate, dimethylarsinate in soil polluted with arsenic. *Soil Sci.* **1982**, *133*, 239–246. [CrossRef]
10. Koch, I.; Wang, L.; Ollson, C.A.; Cullen, W.R.; Reimer, K.J. The predominance of inorganic arsenic species in plants from Yellowknife, Northwest territories, Canada. *Environ. Sci. Technol.* **2000**, *34*, 22–26. [CrossRef]
11. Mattusch, J.; Wennrich, R.; Schmidt, A.C.; Reisser, W. Determination of arsenic species in water, soils and plants. *Fresenius J. Anal. Chem.* **2000**, *366*, 200–203. [CrossRef] [PubMed]
12. Mestrot, A.; Feldmann, J.; Krupp, E.M.; Hossain, M.S.; Roman-Ross, G.; Meharg, A.A. Field fluxes and speciation of arsines emanating from soils. *Environ. Sci. Technol.* **2011**, *45*, 1798–1804. [CrossRef] [PubMed]
13. Ullrich-Eberius, C.I.; Sanz, A.; Novacky, A.J. Evaluation of arsenate- and vanadate-associated changes of electrical membrane potential and phosphate transport in Lemna gibba G1. *J. Exp. Bot.* **1989**, *40*, 119–128. [CrossRef]
14. Farnese, F.S.; Oliveira, J.A.; Farnese, M.S.; Gusman, G.S.; Silveira, M.N.; Siman, L.I. Uptake arsenic by plants: Effects on mineral nutrition, growth and antioxidant capacity. *Idesia* **2014**, *32*, 99–106. [CrossRef]
15. Huang, P.M. Retention of arsenic by hydroxy-aluminum on surface of micaceous mineral colloids. *Soil Sci. Soc. Am. Proc.* **1975**, *39*, 271–278. [CrossRef]
16. Dudas, M.J. Accumulation of native arsenic in acid sulphate soils in Alberta. *Can. J. Soil Sci.* **1987**, *67*, 317–324. [CrossRef]

17. Chiu, V.Q.; Hering, J.G. Arsenic adsorption and oxidation at manganite surfaces. 1. Method for simultaneous determination of adsorbed and dissolved arsenic species. *Environ. Sci. Technol.* **2000**, *34*, 2029–2034. [CrossRef]
18. Jones, C.A.; Langner, H.W.; Anderson, K.; McDermott, T.R.; Inskeep, W.P. Rates of microbially mediated arsenate reduction and solubilization. *Soil Sci. Soc. Am.* **2000**, *64*, 600–608. [CrossRef]
19. Bissen, M.; Frimmel, F.H. Arsenic—A review: Part, I. Occurrences, toxicity, speciation, and mobility. *Acta Hydrochim. Hydrobiol.* **2003**, *31*, 9–18. [CrossRef]
20. Ghosh, A.K.; Bhattacharya, P. Arsenate sorption by reduced and reoxidised rice soils under the infl uence of organic matter amelioration. *Environ. Geol.* **2004**, *45*, 1010–1016. [CrossRef]
21. Moreno-Jiménez, E.; Esteban, E.; Peñalosa, J.M. The Fate of Arsenic in Soil-Plant Systems. In *Reviews of Environmental Contamination and Toxicology, Reviews of Environmental Contamination and Toxicology*; Whitacre, D.M., Ed.; Springer Science+Business Media LLC: New York, NY, USA, 2012; pp. 1–36. [CrossRef]
22. Muller, S.; Daus, B.; Morgenstern, P.; Wennrich, R. Mobilization of antimony and arsenic in soil sediment samples; Evaluation of different leaching procedure. *Water Air Soil Pollut.* **2007**, *183*, 427–436. [CrossRef]
23. Huq, S.M.I.; Naidu, R. Arsenic in groundwater and contamination of the food chain: Bangladesh scenario. In *Natural Arsenic in Groundwater: Occurrence, Remediation and Management*; Bundschuh, J., Ed.; Taylor and Francis Group: New York, NY, USA, 2005; pp. 95–101. [CrossRef]
24. Tlustos, P.; Balik, J.; Szakova, J.; Pavlikova, D. The accumulation of arsenic in radish biomass when different forms of As were applied in the soil. *Rostl. Vyrob.* **1998**, *44*, 7–12.
25. Quaghebeur, M.; Rengel, Z. The distribution of arsenate and arsenite in shoots and roots of Holcus lanatus in influenced by arsenic tolerance and arsenate and phosphate supply. *Plant. Physiol.* **2003**, *132*, 1600–1609. [CrossRef] [PubMed]
26. Raab, A.; Ferreira, K.; Meharg, A.A.; Feldmann, J. Can arsenic-phytochelatin complex formation be used as an indicator for toxicity in Helianthus annuus? *J. Exp. Bot.* **2007**, *58*, 1333–1338. [CrossRef]
27. Szabó, A.; Pokovai, K.; Ragályi, P.; Rékási, M.; Sándor, R.; Bernhardt, B.; Koncz, J.; Kremper, R.; Csathó, P. Nehézfém- és egyéb toxikus mikroelem-terhelés tartamhatása a főtermés mennyiségére szabadföldi kísérletben. *Agrokémia Talajt.* **2019**, *68*, 259–278. [CrossRef]
28. Zhao, F.J.; Ma, J.F.; Meharg, A.A.; McGrath, S.P. Arsenic uptake and metabolism in plants. *New Phytol.* **2009**, *181*, 777–794. [CrossRef]
29. Kádár, I. *The Examination of Heavy Metal Content in Soils and Plants*; Environmental and Nature Conservation Research; Ministry of Environmental Protection and Regional Development; Hungarian Academy of Sciences Institute of Soil Science and Agrochemistry: Budapest, Hungary, 1991.
30. Kabata-Pendias, A. *Trace Elements in Soils and Plants*, 4th ed.; CRC Press: Boca Raton, FL, USA, 2010.
31. Liebig, G.F. Arsenic. In *Diagnostic Criteria for Plants and Soils*; Chapman, H.D., Ed.; University of California: Riverside, CA, USA, 1966; pp. 22–45.
32. Jacobs, L.W.; Syers, J.K.; Keeney, D.R. Arsenic sorption by soils. *Soil Sci. Soc. Am. Proc.* **1970**, *34*, 750–758. [CrossRef]
33. Woolson, E.A.; Axley, J.H.; Kearney, P.C. The chemistry and phytotoxicity of arsenic in soils: 11. Effects of time and phosphorus. *Soil Sci. Soc. Am. Proc.* **1973**, *37*, 254–260. [CrossRef]
34. Kádár, I. *The Contamination of the Soil-Plant-Animal-Human Food Chain with Chemical Elements in Hungary*; KTM; MTA TAKI: Budapest, Hungary, 1995.
35. Kádár, I. *The Environmental Impact of Major Polluting Micronutrients*; MTA ATK Institute of Soil Science and Agrochemistry: Budapest, Hungary, 2012.
36. Ambrose, M.; Smýkal, P.; Singh, N.; Shehadeh, A.; Marcos, T.; Nóbrega, H.; Giovannini, P. *Global Strategy for the Conservation and Use of Pea (Pisum sativum L.) Genetic Resources*; Global Crop Diversity Trust: Bonn, Germany, 2023.
37. Kovács, B.; Puskás-Preszner, A.; Huzsvai, L.; Lévai, L.; Bódi, É. Effect of molybdenum treatment on molybdenum concentration and nitrate reduction in maize seedlings. *Plant Physiol. Biochem.* **2015**, *96*, 38–44. [CrossRef]
38. Várallyay, S.; Kovács, A.B.; Soós, Á.; Kovács, B. Effect of different arsenic-treatments on the dry weight of vegetative plant parts green pea in the different phenophase of the plant development. *Ann. Acad. Rom. Sci. Ser. Agric. Silvic. Vet. Med. Sci.* **2017**, *6*, 144–151.
39. Lakanen, E.; Erviö, R. A comparison of eight extractants for determination of plant available micronutrients in soil. *Acta Agron. Fenn.* **1971**, *123*, 23–232.
40. Kovács, B.; Győri, Z.; Prokisch, J.; Loch, J.; Dániel, P. Studies on soil sample preparation for inductively coupled plasma atomic emission spectrometry analys. *Commun. Soil Sci. Plant Anal.* **2000**, *31*, 1949–1963. [CrossRef]
41. Kovács, B.; Gyôri, Z.; Prokisch, J.; Loch, J.; Dániel, P. A study of plant sample preparation and inductively coupled plasma emission spectrometry parameters. *Commun. Soil Sci. Plant Anal.* **1996**, *27*, 1177–1198. [CrossRef]
42. Soós, Á.; Bódi, É.; Várallyay, S.; Molnár, S.; Kovács, B. Mineral content of propolis tinctures in relation to the extraction time and the ethanol content of the extraction solvent. *LWT-Food Sci. Technol.* **2019**, *111*, 719–726. [CrossRef]
43. Jacobs, L.W.; Keeney, D.R. Arsenic-phosphorus interactions on corn. *Commun. Soil Sci. Plant Anal.* **1970**, *1*, 85–92. [CrossRef]
44. Woolson, E.A. Arsenic phytotoxicity and uptake in six vegetable crops. *Weed Sci.* **1973**, *21*, 524–529. [CrossRef]
45. Filep, G.Y. Talajszennyeződés, talajtisztítás. In *Talajtan*; Stefanovits, P., Filep, G.Y., Füleki, G.Y., Eds.; Mezőgazda Kiadó: Budapest, Hungary, 1999; pp. 363–381.

46. Szegedi, L.; Bélteki, I.; Fodorné Fehér, E. A talaj és növények arzén tartalmának összefüggés vizsgálata nehézfém terheléses tartamkísérletben. *Acta Carolicus Roberticus* **2013**, *3*, 135–144.
47. Szabó, A.; Pokovai, K.; Ragályi, P.; Rékási, M.; Sándor, R.; Bernhardt, B.; Koncz, J.; Kremper, R.; Csathó, P. Nehézfém- és egyéb toxikus mikroelem-terhelés tartamhatása a talajból mért visszanyerési százalékuk alakulására szabadföldi kísérletekben. *Agrokémia Talajt.* **2019**, *68*, 293–314. [CrossRef]
48. Szabó, A.; Pokovai, K.; Ragályi, P.; Rékási, M.; Sándor, R.; Bernhardt, B.; Koncz, J.; Haszon, B.; Kremper, R.; Csathó, P. Nehézfém- és egyéb toxikus mikroelem-terhelés tartamhatása a talaj károselem alakulására, szabadföldi kísérletben. *Acta Agron. Óváriensis* **2019**, *60*, 52–89.
49. Violante, A.; Del Gaudio, S.; Pigna, M.; Pucci, M.; Amalfinato, C. Sorption and desorption of arsenic by soil minerals and soils in the presence of nutrients and organics. In *Interactions of Soil Minerals, Organic Matter and Microorganism in Soils*; Huang, Q., Violante, A., Huang, P.M., Eds.; Springer-Verlag: New York, NY, USA, 2008; pp. 39–69. [CrossRef]
50. MacPheel, A.W.; Chisholm, D.; MacEachern, C.R. The persistence of certain pesticides in the soil and their effect on crop yields. *Can. J. Soil Sci.* **1960**, *40*, 59–63. [CrossRef]
51. Porter, E.K.; Peterson, P.J. Arsenic accumulation by plants on mine waste, United Kingdom. *Sci. Total Environ.* **1975**, *4*, 365–368. [CrossRef]
52. Lyubun, Y.V.; Kosterin, P.V.; Zakharova, E.A.; Shcherbakov, A.A.; Fedorov, E.E. Arsenic-contaminated soils phytotoxicity studies with sunflower and sorghum. *J. Soils Sediments* **2002**, *2*, 143–147. [CrossRef]
53. Melo, E.E.C.; Costa, E.T.S.; Guilherme, L.R.G.; Faquin, V.; Nascimento, C.W.A. Accumulation of arsenic and nutrients by castor bean plants grown on an As-enriched nutrient solution. *J. Hazard. Mater.* **2009**, *168*, 479–483. [CrossRef] [PubMed]
54. Kumar, D.; Singh, V.P.; Tripathi, D.K.; Prasad, S.M.; Chauhan, D.K. Effect of arsenic on growth, arsenic uptake, distribution of nutrient elements and thiols in seedlings of Wrightia arborea (Dennst.) Mabb. *Int. J. Phytoremediat.* **2015**, *23*, 128–134. [CrossRef]
55. Raab, A.; Feldmann, J.; Meharg, A.A. The nature of arsenic-phytochelatin complexes in *Holcus lanatus* and *Pteris cretica*. *Plant Physiol.* **2004**, *134*, 1113–1122. [CrossRef]
56. Wells, B.R.; Gilmor, J.T. Sterility in rice cultivars as influenced by MSMA rate and water management. *Agron. J.* **1977**, *69*, 451–454. [CrossRef]
57. Liu, Q.; Hu, C.; Tan, Q.; Sun, X.; Su, J.; Liang, Y. Effects of As on As uptake, speciation, and nutrient uptake by winter wheat (*Triticum aestivum* L.) under hydroponic conditions. *J. Environ. Sci.* **2008**, *20*, 326–331. [CrossRef]
58. Smith, S.E.; Christophersen, H.M.; Pope, S.; Smith, F.A. Arsenic uptake and toxicity in plants: Integrating mycorrhizal influences. *Plant Soil* **2010**, *327*, 1–21. [CrossRef]