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Occurrence of Pharmaceuticals and Personal Care Products in *Cannabis sativa* L. Following Application of Sewage Sludge-Based Composts and Vermicomposts

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Abstract: The use of some organic fertilizers may raise concerns about the transfer of hazardous substances to soil and plants. This study examined the impact of soil amendment with compost and vermicompost derived from sewage sludge and straw pellets in different ratios on the accumulation of pharmaceuticals and personal care products (PPCPs) by hemp (*Cannabis sativa* L.). The concentrations of fifty different PPCPs were measured in compost-treated soil, and in the roots and above-ground biomass of cannabis grown on the soil. The highest bioaccumulation of PPCPs was recorded in plants from previously unfertilized soils low in organic matter, while the lowest concentrations were measured in soil amended with compost or vermicompost made from straw pellets only, without sewage sludge. The effect of sludge-derived compost and vermicompost application on the absorption of PPCPs was statistically determined by measurements in soil samples, roots and shoots of carbamazepine, cetirizine, lamotrigine, telmisartan, paraxanthine, tramadol, triclosan, and venlafaxine. The above-ground biomass exhibited lower PPCP content than roots, suggesting a potential plant defense mechanism for limiting contaminant translocation. Only tramadol and carbamazepine showed significantly increased content in above-ground biomass.

Keywords: above-ground biomass; *Cannabis sativa* L.; compost; personal care products; pharmaceuticals; roots; sewage sludge; soil; vermicompost

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1. Introduction

Population growth, increased use of pharmaceuticals and personal care products (PPCPs), and wastewater treatment limitations contribute to environmental pollution. Farmers also reintroduce organic matter into the soil, which may carry harmful micropollutants. Effective strategies are needed to reduce these contaminants and protect environmental and agricultural sustainability [1,2].

The application of sewage sludge in agriculture garnered significant attention due to its potential to enhance soil fertility while simultaneously addressing waste management challenges. The European urban wastewater treatment directive mandated the exploration of sustainable practices for sewage sludge utilization, particularly aimed at organic farmers [3]. However, the presence of contaminants, including pharmaceuticals and personal care products, raises concerns regarding the safety of crops fertilized with sludge and the potential for bioaccumulation in the food chain [4]. PPCPs, which encompass a wide range of substances, including hormonally active compounds, have been detected in appreciable amounts in crop soil and runoff water following the application of treated sewage sludge [5].

Hemp (*Cannabis sativa* L.) emerged as a promising crop for the sustainable use of organic amendments, given its rapid growth and ability to thrive under diverse soil conditions [6]. The cultivation of hemp not only contributes to agricultural diversity, but also offers potential economic benefits through its application in textiles, biofuels, and health products [7]. Previous studies indicated that the application of organic amendments can influence the bioavailability of contaminants in soil, thereby affecting their uptake by plants [8,9].

The utilization of compost and vermicompost derived from sewage sludge can significantly affect the concentration of PPCPs in agricultural soils. Composting has been shown to reduce the concentration of certain contaminants; however, the effectiveness of this process varies depending on the specific PPCPs and composting conditions. Recent research [10] demonstrated that composting can significantly reduce the levels of caffeine, citalopram, diclofenac, mirtazapine, venlafaxine, and partially sulfapyridine, while compounds such as amitriptyline, carbamazepine, cetirizine, ibuprofen, telmisartan, and triclosan were more resistant to degradation. The microbial community dynamics, physicochemical conditions, and organic matter composition in composting influence the breakdown efficiency of these contaminants. Vermicomposting, which involves the activity of earthworms to decompose organic matter, has been reported to enhance the degradation of PPCPs. The role of earthworms in the biotransformation and bioaccumulation of PPCPs has been extensively studied, with some compounds showing increased degradation efficiency in their presence. In another study [11], it was found that vermicomposting facilitated the removal of triclosan (37%) and mirtazapine (14%) and demonstrated earthworm influence on the degradation of venlafaxine, citalopram, and diclofenac. The study highlighted that earthworms contribute to PPCP degradation through enzymatic activities and bioaccumulation, but the extent of this removal varies depending on the specific PPCP. Despite these findings, significant knowledge gaps remain regarding the overall efficiency of composting and vermicomposting in PPCP degradation. Some PPCPs may undergo transformation rather than complete degradation, leading to the formation of intermediate metabolites whose environmental impact is not yet fully understood.

While hemp (*Cannabis sativa* L.) has been widely studied for its ability to accumulate heavy metals from contaminated soils, research on its effectiveness in remediating organic pollutants such as PPCPs remains limited. The remediation potential of hemp for pollutants, particularly heavy metals, gained considerable attention due to its unique biological properties and adaptability to a variety of environmental conditions. As a promising candidate for phytoremediation, hemp demonstrated significant capability in taking up and accumulating heavy metals, such as cadmium (Cd), lead (Pb), and zinc (Zn), from contaminated soils. Research indicates that planting a hemp crop can effectively remediate soils contaminated with these metals [12–14]. The mechanisms involved in the process of phytoextraction, where contaminants are absorbed through the roots and translocated to the shoots, allowing for easy harvesting of the biomass, are still being investigated [15,16]. Hemp's growth characteristics, including its deep root system and rapid biomass production, enhance its effectiveness in phytoremediation. Studies have shown that these traits contribute to the plant's ability to thrive in contaminated environments, making it a suitable candidate for soil decontamination [17,18]. However, the implications of using conventional compost and vermicompost derived from sewage sludge on the uptake of PPCPs by hemp have been inadequately explored.

In this study, we aimed to investigate the effects of composted and vermicomposted sewage sludge combined with different amounts of straw pellets on the concentrations of PPCPs in both soil and hemp plants (roots and above-ground biomass). In achieving this goal, the following hypotheses were formulated:

H1: The application of composts and vermicomposts increases the content of PPCPs in *Cannabis sativa* L.

H2: There are significant differences in PPCP content between plants grown with and without composts and vermicomposts.

H3: For certain PPCPs, there are significant differences in accumulation between roots and in above-ground biomass of *Cannabis sativa* L.

H4: Hemp has phytoremediation potential for PPCPs.

2. Materials and Methods

Composts and vermicomposts were first prepared for fertilizing the hemp plants in the pot experiment. The input raw materials for these fertilizers included dewatered unstabilized sludge from the wastewater treatment plant of a small town with an average load of 3500 EO (equivalent inhabitants) and moistened straw pellets prepared by adding 1 kg of dry pellets to 4 L of water at 60 °C to improve degradability and disintegrability before experimental use.

Composting was performed with five different weight combinations of dewatered sewage sludge (SS) and moistened straw pellets (SP): (T1) 100% SS; (T2) 75% SS + 25% SP; (T3) 50% SS + 50% SP; (T4) 25% SS + 75% SP; and (T5) 100% SP with each treatment being repeated twice. Total weight of composted material in each repetition of each treatment was 45 kg. The material was composted for four months in an aerobic composter with a working volume of 70 L and a radius of 23 cm. For the first two weeks, the mixture was aerated for 5 min every half hour at an intensity of 4 L/min and then for 2. 5 min every half hour at the same intensity. Three samples were taken from each repetition, a total of 6 samples for analysis. Composting, however, is not the point of this article. Here, only the resulting final composts were used as fertilizer.

The vermicomposting was performed in five of the same treatments as composting mentioned above with fresh raw materials and in five treatments with two weeks pre-composted raw materials. Each treatment was established in 3 repetitions. Nine kilograms of raw materials and 3 L of substrate with earthworms were placed into each vermicomposting tray. In all treatments, nine kilograms of raw material were transferred to worm bins (40 × 40 × 15 cm) for 120 days of vermicomposting. The substrate (3 L grape marc) containing earthworms was placed into the tray from the side to avoid earthworm mortality. The epigeic *Eisenia andrei* species was used. The average density of earthworms in the substrate was 126 pieces per liter. The vermicomposting process was carried out at a constant temperature of 22 °C. The moisture level of the material was maintained at around 70–80%.

The vegetative pot experiment was established in May 2021. It was carried out with 15 different fertilization treatments and one control treatment. All treatments were repeated three times, in three pots. Soil Chernozem (pH = 7.3; EC = 0.11 mS/cm; P = 54 mg/kg;

K = 370 mg/kg; Ca = 5700 mg/kg; and Mg = 193 mg/kg) was placed in each pot and mixed with compost and vermicompost according to the scheme in Table 1.

Table 1. Scheme of the vegetative pot experiment.

Treatment #	Fertilizer	Soil in Pot (kg Dry Matter)	Used Fertilizer in Pot (g Fresh Matter)	Recalculation of Used Fertilizer on Dry Matter (g)
1	Control—soil only	5	0	0
2	Compost 1 (sludge 100%, straw pellets 0%)	5	337	40
3	Compost 2 (sludge 75%, straw pellets 25%)	5	322	40
4	Compost 3 (sludge 50%, straw pellets 50%)	5	320	40
5	Compost 4 (sludge 25%, straw pellets 75%)	5	312	40
6	Compost 5 (sludge 0%, straw pellets 100%)	5	264	40
7	Vermicompost f. f. 1 (sludge 100%, straw pellets 0%)	5	139	40
8	Vermicompost f. f. 2 (sludge 75%, straw pellets 25%)	5	161	40
9	Vermicompost f. f. 3 (sludge 50%, straw pellets 50%)	5	199	40
10	Vermicompost f. f. 4 (sludge 25%, straw pellets 75%)	5	207	40
11	Vermicompost f. f. 5 (sludge 0%, straw pellets 100%)	5	255	40
12	Vermicompost p. f. 6 (sludge 100%, straw pellets 0%)	5	175	40
13	Vermicompost p. f. 7 (sludge 75%, straw pellets 25%)	5	188	40
14	Vermicompost p. f. 8 (sludge 50%, straw pellets 50%)	5	185	40
15	Vermicompost p. f. 9 (sludge 25%, straw pellets 75%)	5	168	40
16	Vermicompost p. f. 10 (sludge 0%, straw pellets 100%)	5	235	40

f. f. = vermicompost made of fresh feedstock. p. f. = vermicompost made of pre-composted feedstock.

After filling with the appropriate mixture, seven hemp seeds (*Cannabis sativa* L., variety Kompolti) were sown in each pot, and after emergence, thinned to three plants. The plants were grown under a sliding roof and watered with demineralized water twice a day. The plants were harvested three months after sowing, and divided into above-ground parts and roots, which were dried at 30 °C and ground. The soil after removal of roots was dried for 2 weeks at room temperature, homogenized, and passed through a sieve with a 2 mm mesh.

The soil and plant samples were extracted with methanol at an elevated pressure of 10.3 MPa and a temperature of 80 °C in a Dionex ASE 200 solvent extractor (Dionex Corporation, Sunnyvale, CA, USA). From 1 to 5 g of sample was placed in the extraction cartridge and the cartridge was filled with washed sea sand. Three extraction cycles with 5 min static steps at the beginning of each cycle were conducted. The extracts were evaporated to a volume of about 5 mL and centrifuged at 6000× g for 10 min. The liquid chromatography–mass spectrometry (LC/MS) method was used to identify and quantitate fifty PPCPs (Table 2).

Statistical evaluation of the data was performed in the Statistica 12 program and in Microsoft Excel Office 16. The measured values of the concentrations of the detected PPCPs were tested based on the wording of the hypotheses using various methods. The test was performed at a confidence level of $\alpha = 0.05$. Due to the rejection of the normality of the data, the one-factor non-parametric ANOVA method, i.e., the Kruskal–Wallis H test, was used in the case of the first and second hypotheses (H1, H2). In the case of the third hypothesis (H3), also due to the failure to meet the normality of the data, the Wilcoxon non-parametric test was chosen to compare the mean values and frequencies of two dependent sets: roots and above-ground biomass. To evaluate the influence of individual variants of the experiment, a comparison of means and standard deviations was chosen.

The phytoremediation hypothesis (H4) was evaluated according to the following equations [19,20]:

$$TC = Cp/Cs$$

where TC is the transfer coefficient, which evaluates the relationship between the contaminant concentration in the plant, Cp, and the concentration in the soil, Cs. If the coefficient is >1, the plant has the potential for successful use in phytoremediation.

$$TF = Cag/Cr$$

where TF is the translocation factor, which indicates the relationship between the contaminant concentration in the above-ground biomass, Cag, and the concentration in the plant roots, Cr. If TF >1, these plants have a greater ability to accumulate contaminants.

$$PPI = Cp/CpRef$$

where PPI is the plant contamination index expressing the relationship between Cp, and the same plant species grown on non-contaminated soil, CpRef, which is also the reference value for non-contaminated soil.

Table 2. List of PPCPs analyzed in this study.

Group	Purpose of the Products	PPCPs
Pharmaceuticals	NSAIDs and analgesics	ibuprofen, diclofenac, naproxen, acetaminophen = paracetamol, ketoprofen, tramadol, trimethoprim, erythromycin, sulfamethoxazole
	Antibiotics	azithromycin, clarithromycin, sulfamethazine, sulfapyridine, sulfanilamide
	Antidepressants	amitriptyline, venlafaxine, citalopram, mirtazapine
	Antihistamines	cetirizine
	Antiepileptics	lamotrigine, carbamazepine, gabapentin
	Antimycotics	fluconazole
	Diuretics	furosemide, hydrochlorothiazide
	Cholesterol regulators	atorvastatin
	β—blockers	atenolol, metoprolol, 17 α-estradiol, 17 β-estradiol, estriol, estrone,
	Hormones	norgestrel, norethindrone, genistein, equol, daidzein, equilin, ethinylestradiol, zearalenol
	Contrast agents for X-ray	iomeprol
	Substances used in food and supplements; sugar substitutes	acesulfame, caffeine, saccharin, paraxanthine (metabolite)
	Others	omeprazole, telmisartan
Personal care products	Antibacterial and antifungal agents	triclosan
Endocrine disruptors	Additives for plastics	bisphenol A, bisphenol F

3. Results

Based on the measurement data, 14 PPCPs out of a total of 50 tested PPCPs were detected in the samples (Table 3). The measured concentrations of caffeine, carbamazepine, daidzein, genistein, paraxanthine, telmisartan, and tramadol were detected in all three groups of samples, in the soil, in the roots, and in the above-ground parts of the plants.

Table 3. Detected (x) PPCPs in soil, roots and above-ground biomass.

Samples	Detected PPCPs													
	Caffeine	Carbamazepine	Cetirizine	Daidzein	Diclofenac	Equol	Estron	Genistein	Lamotrigine	Paraxanthine	Telmisartan	Tramadol	Triclosan	Venlafaxine
Soil	x	x	-	x	x	x	x	x	x	x	x	x	x	-
Roots	x	x	x	x	-	x	x	x	-	x	x	x	x	x
Above-ground biomass	x	x	-	x	x	-	-	x	-	x	x	x	-	-

3.1. The Effect of Compost and Vermicompost Application on the Content of PPCPs in Soil

In addition to the above-mentioned variants, the analysis and testing also included the input (initial) soil, referred to as "IS", which represents a soil sample used for the experiment. The effect of the application of composted or vermicomposted sludge on the content of selected PPCPs in the soil was tested using a one-factor, non-parametric ANOVA method.

It should be noted that non-parametric testing is very stringent, so seemingly clear differences may indicate acceptance of the null hypothesis. A significant effect of compost and vermicompost fertilization on increases in lamotrigine and telmisartan concentration in the soil was recorded (Table 4). In the case of carbamazepine, this effect was seen only with compost application. Although a statistically significant difference was not demonstrated for paraxanthine (the measured p value was close to the significance level), an effect of fertilizer application was manifested by several readings, mostly outliers. For daidzein, the difference in concentration was statistically significant, but the comparison between the input soil with and without fertilizer showed only a slight change. For the other detected PPCPs, no significant difference was demonstrated between the measured concentrations in the input soil, soil without additions, and soil where fertilizer was applied.

Table 4. Comparison of the average values of the contents of chosen PPCPs in the soil under the experimental conditions.

Variants	Caffeine	Carbamazepin	Daidzein	Diclofenac	Equol	Estron	Genistein	Lamotrigine	Paraxanthine	Telmisartan	Tramadol	Triclosan
	[ng/g]											
Initial soil	4.91 a	0.00 a	0.42 a	0.38 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.23 a	0.52 a
1	4.73 a	0.00 a	0.00 b	0.23 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.00 a	0.23 a	0.00 a
2	5.30 a	0.78 b	0.19 ab	0.08 a	0.00 a	0.00 a	0.00 a	0.40 b	0.00 a	6.09 b	0.46 a	0.25 a
3	4.64 a	0.27 a	0.26 b	0.79 a	0.00 a	0.00 a	0.00 a	0.06 a	0.00 a	1.37 c	0.42 a	0.00 a
4	4.54 a	0.00 a	0.00 a	0.18 a	0.00 a	0.00 a	0.00 a	0.14 a	0.23 a	1.44 c	0.44 a	0.63 a
5	4.65 a	0.00 a	0.12 ab	0.37 a	5.06 a	0.00 a	0.00 a	0.22 a	0.00 a	1.67 c	0.12 a	0.11 a
6	5.07 a	0.00 a	0.16 ab	0.26 a	0.00 a	0.00 a	0.00 a	0.04 a	0.33 a	0.18 a	0.15 a	0.00 a
7	4.11 a	0.00 a	0.80 c	0.00 a	0.00 a	0.00 a	0.00 a	0.09 a	0.22 a	0.58 a	0.11 a	0.00 a
8	4.26 a	0.00 a	0.17 ab	0.51 a	0.00 a	0.00 a	0.00 a	0.07 a	0.13 a	0.83 a	0.16 a	0.19 a
9	4.76 a	0.00 a	0.00 b	0.29 a	0.00 a	0.00 a	0.00 a	0.06 a	0.37 a	0.56 a	0.00 a	0.17 a
10	2.51 a	0.00 a	0.24 ab	0.34 a	0.00 a	0.00 a	0.00 a	0.00 a	0.23 a	0.27 a	0.00 a	0.58 a

Table 4. *Cont.*

Variants	Caffeine	Carbamazepin	Daidzein	Diclofenac	Equol	Estron	Genistein	Lamotrigine	Paraxanthine	Telmisartan	Tramadol	Triclosan
	[ng/g]											
11	2.76 a	0.00 a	0.55 a	0.16 a	0.00 a	0.00 a	0.00 a	0.05 a	0.26 a	0.12 a	0.00 a	0.42 a
12	4.72 a	0.00 a	0.13 b	0.00 a	0.00 a	0.00 a	0.00 a	0.11 a	0.15 a	0.89 c	0.41 a	0.00 a
13	4.42 a	0.00 a	0.12 b	0.05 a	0.00 a	0.00 a	0.00 a	0.13 a	0.00 a	0.78 a	0.17 a	0.76 a
14	5.01 a	0.00 a	0.54 a	0.34	0.00 a	0.00 a	0.00 a	0.12 a	0.20 a	0.50 a	0.25 a	0.00 a
15	5.26 a	0.00 a	0.33 a	0.47	0.00 a	0.23 a	0.27 a	0.06 a	0.21 a	0.35 a	0.27 a	0.14 a
16	5.06 a	0.00 a	0.43 a	0.33	0.00 a	0.00 a	0.00 a	0.07 a	1.05 a	0.65 a	0.06 a	0.00 a
Average	4.51	0.06	0.44	0.28	0.30	0.01	0.02	0.10	0.20	0.96	0.21	0.22

Different letters in a column indicate significant differences among layers (Kruskal–Wallis test, $p \leq 0.05$).

For equol, estrone, and genistein, only one value was measured out of all 50 samples (including three samples of input soil). When comparing the average values of the concentrations of individual PPCPs for all variants, the highest values across all groups were recorded for caffeine. The increase in the content in soils after fertilizer application was proven particularly for telmisartan, then paraxanthine, and lastly, lamotrigine.

3.2. Effect of Compost and Vermicompost Application on PPCP Content in Hemp

In measuring the PPCP concentrations of the collected plant samples, the values for above-ground biomass and roots were determined separately.

3.2.1. Effect of Compost and Vermicompost Application on the Content of PPCPs in Roots

The same number of PPCPs was recorded in the roots as in the surrounding soil, but they were not the same PPCPs. Hypothesis H2 states: There are significant differences between the contents of these PPCPs in the roots of plants grown with or without the addition of compost or vermicompost. Compared with the soil, we did not find diclofenac or lamotrigine in the roots, but cetirizine and venlafaxine were detected. Table 5 lists the conclusions on hypothesis H2 in connection with plant roots. A statistically significant difference was demonstrated for most PPCPs.

It can be stated that for four out of twelve detected PPCPs, the application of composts and vermicomposts had an effect on the PPCP content in the roots. A noticeable difference can be observed for the PPCPs carbamazepine and cetirizine. In the case of tramadol, triclosan, and venlafaxine, although no statistically significant difference was demonstrated, isolated occurrences of the detected PPCPs were observed in the roots of plants on soils fertilized with vermicompost. The other compounds observed in roots were detected mainly in plants grown on soils without the addition of fertilizer. For example, daidzein, estrone, and genistein were mostly significantly higher than in plants grown on fertilized soils. Caffeine, equol, and paraxanthine were found in the roots of plants in soils both with and without fertilizer. As with soil testing, a comparison of the average values for the individual soil variants was made. This overview shows a trend where high values were recorded in the control variant for daidzein, equol, estrone, and genistein. In many fertilized variants, the highest concentration among the monitored PPCPs was for telmisartan.

Table 5. Comparison of the average contents of selected PPCPs in the roots.

Variants	Caffeine	Carbamazepin	Cetirizine	Daidzein	Equol	Estron	Genistein	Paraxanthine	Telmisartan	Tramadol	Triclosan	Venlafaxine
						[ng/g]						
1	24.7 a	0.0 a	0.0 a	533.2 a	112.6 a	187.8 a	197.2 a	14.6 a	0.4 a	0.0 a	0.0 a	0.0 a
2	0.0 b	0.2 a	0.0 a	0.0 b	115.6 a	0.0 b	0.0 b	0.0 b	134.4 b	0.0 a	0.0 a	0.0 a
3	0.0 b	0.4 a	0.0 a	0.0 b	109.1 a	0.0 b	0.0 b	0.0 b	35.3 ab	0.0 a	0.0 a	0.0 a
4	0.0 b	0.6 ab	0.0 a	0.0 b	58.4 a	0.0 b	0.0 b	0.0 b	73.9 b	0.0 a	0.0 a	0.0 a
5	0.0 b	0.4 a	0.3 a	0.0 b	214.6 b	0.0 b	0.0 b	0.0 b	158.2 b	0.0 a	0.0 a	0.0 a
6	32.1 a	0.0 a	0.0 a	0.0 b	16.1 c	0.0 b	0.0 b	1.1 b	5.4 a	0.0 a	0.0 a	0.0 a
7	0.0 b	1.1 ab	1.4 a	0.0 b	75.2 a	0.0 b	0.0 b	0.0 b	154.4 b	0.0 a	8.6 a	0.0 a
8	15.3 ab	1.2 ab	2.2 b	0.0 b	86.7 a	0.0 b	0.0 b	4.1 b	616.9 c	0.1 a	9.3 a	0.2 a
9	0.0 b	0.4 a	1.1 ab	0.0 b	77.3 a	0.0 b	0.0 b	0.0 b	143.3 b	0.0 a	0.0 a	0.0 a
10	0.0 b	0.4 a	0.0 a	0.0 b	79.3 a	0.0 b	0.0 b	9.2 a	67.0 b	0.0 a	0.0 a	0.0 a
11	0.0 b	0.0 a	0.1 a	0.0 b	55.3 ac	0.0 b	0.0 b	0.0 b	3.1 a	0.0 a	0.0 a	0.0 a
12	0.0 b	0.9 a	2.2 b	0.0 b	74.0 a	0.0 b	0.0 b	7.6 a	30.0 a	0.1 a	0.6 a	20.6 a
13	0.0 b	1.6 b	2.9 b	0.0 b	29.1 c	0.0 b	0.0 b	4.2 b	187.9 b	0.0 a	2.5 a	0.0 a
14	0.0 b	0.5 a	0.6 a	0.0 b	109.5 a	0.0 b	0.0 b	0.0 b	112.4 b	0.0 a	1.8 a	0.0 a
15	0.0 b	0.2 a	0.0 a	0.0 b	61.9 a	0.0 b	0.0 b	0.0 b	55.2 b	0.0 a	0.0 a	0.0 a
16	0.0 b	0.0 a	0.0 a	0.0 b	72.0 a	0.0 b	0.0 b	8.8 a	4.7 a	0.0 a	0.0 a	0.0 a
Average	4.5	0.5	0.7	33.3	84.2	11.7	12.3	3.1	111.4	0.01	1.4	1.3

Different letters in a column indicate significant differences among layers (Kruskal–Wallis test, $p \leq 0.05$).

3.2.2. Effect of Compost and Vermicompost Application on PPCP Concentration in Above-Ground Biomass

The fewest types of PPCPs from all three groups of samples were detected in the above-ground biomass (Table 6). Out of a total of 14 PPCPs captured, only eight were recorded in the above-ground biomass. As with plant roots, a one-factor non-parametric ANOVA was used for above-ground biomass and conclusions for hypothesis H2 were drawn.

The results show a significant difference between the concentration of the detected PPCPs in the soil without additives and in the soil after the application of compost or vermicompost. However, demonstrable differences were recorded especially for caffeine, daidzein, genistein, and paraxanthine where the plants absorbed more PPCPs from the soil without additives than from fertilized soils. Higher accumulation of the studied PPCPs by plants in fertilized soils was recorded especially for PPCPs without a statistically proven difference in content, namely carbamazepine and telmisartan. In both cases, however, the *p* values were close to demonstrating a statistically significant difference. In the case of tramadol, the frequency of occurrence of measured values was very low, which, however, indicated an increased uptake of the substance by plants after the application of compost. As in the previous root testing, a comparison of the average values for the individual variants was made. In this case, the highest values were also measured, especially in plants growing on control soil, without the addition of fertilizer, especially for daidzein, genistein, caffeine, and paraxanthine.

Table 6. Comparison of the average concentrations of selected PPCPs in the above-ground biomass according to the experimental condition.

Variants	**Caffeine**	**Carbamazepin**	**Daidzein**	**Diclofenac**	**Genistein**	**Paraxanthine**	**Telmisartan**	**Tramadol**
				[ng/g]				
1	14.1 a	0.00 a	98.20 a	1.54 ab	20.81 a	9.42 a	0.15 a	0.00 a
2	0.00 a	1.39 a	0.00 b	2.28 a	0.00 b	0.00 b	0.68 a	0.10 ab
3	0.00 a	0.80 a	0.00 b	2.40 a	0.00 b	0.00 b	0.09 a	0.00 a
4	9.33 a	0.62 a	0.00 b	1.49 ab	0.00 b	4.04 ab	0.32 a	0.26 b
5	0.00 a	0.43 a	0.00 b	1.53 ab	0.00 b	2.82 b	0.00 a	0.00 a
6	0.00 a	0.00 a	0.00 b	1.41 ab	0.00 b	0.00 b	0.76 a	0.00 a
7	0.00 a	1.24 a	0.00 b	0.65 c	0.00 b	0.00 b	0.18 a	0.00 a
8	0.00 a	1.06 a	0.00 b	1.20 ab	0.00 b	0.00 b	0.26 a	0.00 a
9	0.00 a	0.83 a	0.00 b	2.32 a	0.00 b	0.00 b	0.08 a	0.00 a
10	0.00 a	0.50 a	0.00 b	2.35 a	0.00 b	0.00 b	0.08 a	0.00 a
11	0.00 a	0.00 a	0.00 b	0.81 c	0.00 b	0.00 b	0.32 a	0.00 a
12	0.00 a	1.69 a	0.00 b	0.00 c	0.00 b	0.00 b	0.27 a	0.00 a
13	0.00 a	1.52 a	0.00 b	0.00 c	0.00 b	0.00 b	0.63 a	0.00 a
14	0.00 a	0.49 a	0.00 b	0.00 c	0.00 b	0.00 b	0.87 a	0.00 a
15	9.23 a	0.25 a	0.00 b	0.00 c	0.00 b	0.52 b	0.39 a	0.00 a
16	0.00 a	0.00 a	0.00 b	0.00 c	0.00 b	0.00 b	0.29 a	0.00 a
Average	2.89	0.12	1.38	0.51	0.11	0.74	0.22	0.02

Different letters in a column indicate significant differences among layers (Kruskal–Wallis test, $p \leq 0.05$).

3.2.3. Differences in PPCP Content Between Roots and Above-Ground Biomass

The third hypothesis (H3) required testing whether there were statistically significant differences in the content of detected PPCPs between under-ground and above-ground parts of hemp plants based on the mean values and frequencies of occurrence. Due to the lack of normality of the data, the Wilcoxon non-parametric test was used to compare the medians and frequencies of two dependent sets. The input data of the test are given in Table 7.

According to the test result at the 5% significance level with a Z value of 2.691 and a p value of 0.007, a significant difference in the concentration of a PPCP between roots and above-ground biomass was demonstrated. The extreme value of daidzein (533 ng/g), which is significantly different from the other values, represents the mean concentration in the roots. It was also found that 50% of the values of the detected compounds lie between 1.70 and 119 ng/g. In the case of above-ground biomass, two extreme values can be seen, which represent the mean values of the concentrations of daidzein, with a median value of 98.2 ng/g, and caffeine with a median value of 32.6 ng/g. The outlier is genistein with a median value of 20.8 ng/g, where 50% of the values were between 0 and 7.20 ng/g.

According to the result of the Wilcoxon paired test with a Z value of 1.73 and a p value of 0.083, it was found that at the 5% significance level there were no significant differences in the frequency of occurrence of PPCPs between the roots and above-ground biomass of cannabis plants. However, if a higher significance level ($\alpha = 0.1$) is chosen, the difference could be significant. In comparing the frequencies of occurrence of PPCPs between the roots and above-ground biomass, a significantly smaller difference was observed compared to the median concentrations.

Table 7. Input data of medians and frequencies for the Wilcoxon test.

PPCPs	Roots		Above-Ground Biomass	
	Median [ng/g]	Frequency	Median [ng/g]	Frequency
Caffeine	43.2	5	32.6	3
Carbamazepine	0.70	34	0.90	36
Cetirizine	1.71	19	0.00	0
Daidzein	533	3	98.1	3
Diclofenac	0.00	0	2.07	26
Equol	87.8	46	0.00	0
Estron	187	3	0.00	0
Genistein	197	3	20.8	3
Paraxanthine	13.5	11	7.20	7
Telmisartan	118	45	0.52	31
Tramadol	0.29	2	0.36	3
Triclosan	7.61	9	0.00	0
Venlafaxine	20.7	3	0.00	0

3.3. Influence of Individual Experimental Variants on PPCP Content

The results of the analyses were subjected to a more detailed evaluation of the influence of individual soil variants on the concentration of micropollutants in each group (Figure 1). The amounts of micropollutants measured in plant roots appear to be the highest of all three groups of samples. Most of the measurements on plant roots are in the tens and sometimes even hundreds of ng/g of dry matter, and therefore, we conclude that the greatest accumulation of micropollutants occurred in the underground biomass. In contrast, the PPCP concentrations in the soil and the above-ground biomass were orders of magnitude lower, but large differences are evident in the control, or soil without added fertilization; the values measured in the soil were much lower than in roots or above-ground biomass.

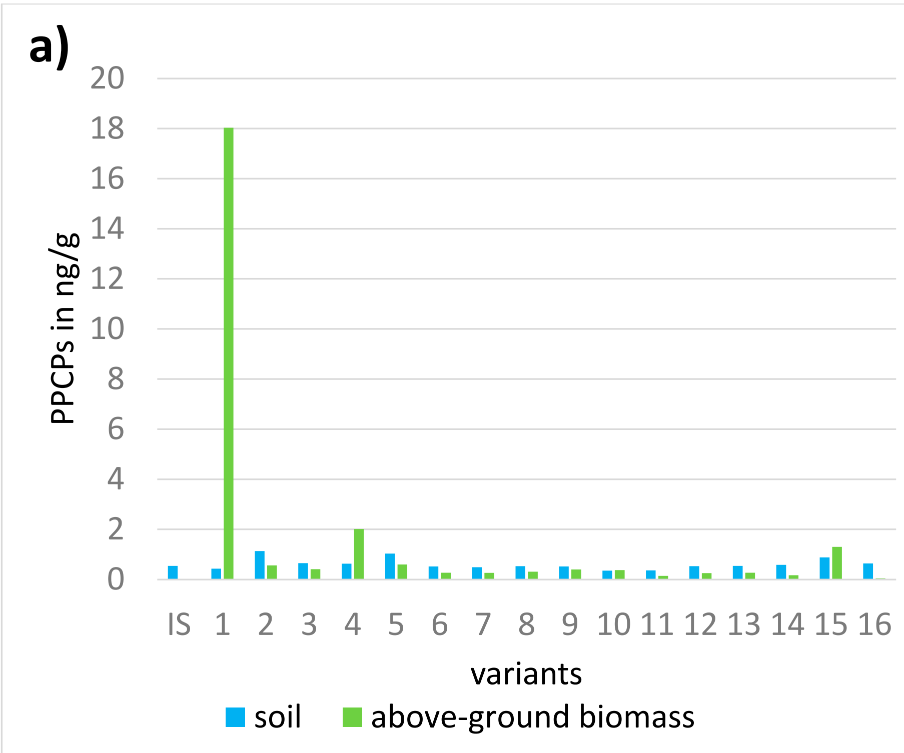

Figure 1. *Cont.*

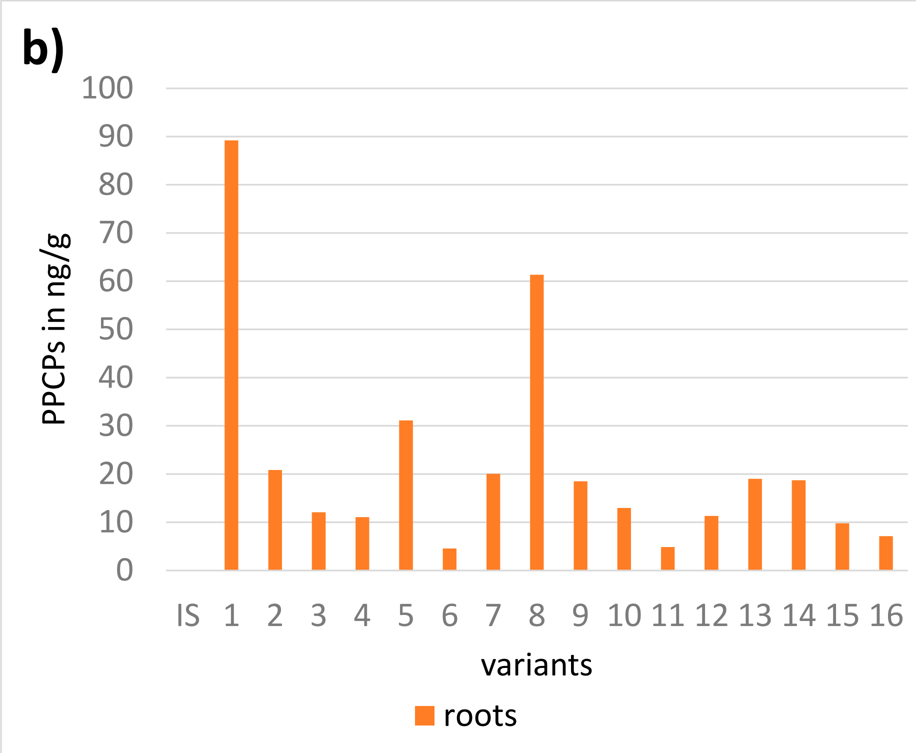

Figure 1. Effect of variants on PPCP content in soil, above-ground biomass (**a**) and roots (**b**).

3.3.1. Influence of Fertilization Variants on the Content of Micropollutants in the Soil

The results of the detailed analysis show high caffeine values, which were particularly evident in soils fertilized with pre-composted vermicompost, mainly in variants with a higher addition of pellets (Table 4). However, the highest caffeine value (5.3 ± 0.78 ng/g) was measured in soil fertilized with compost from 100% sewage sludge (no straw pellets). Significant values were recorded for telmisartan in soil fertilized with compost made from sewage sludge, but again, the highest occurred with 100% sewage sludge addition (6.09 ± 0.97 ng/g telmisartan). Overall, the highest values were observed in variant no. 2, i.e., in soil with the addition of compost based on 100% sewage sludge. In this case the average value for all detected micropollutants was 1.13 ± 2.06 ng/g dry matter. In contrast, the lowest concentration values for the detected compounds were observed in variant no. 10 (vermicompost based on 25% sludge/75% straw pellets) and no. 11 (vermicompost based on 100% straw pellets).

3.3.2. Effect of Fertilization Variants on the Content of Micropollutants in Plant Roots

A detailed analysis of the effect of variants on the content of PPCPs in roots (Table 5) revealed an almost identical trend as in the above-ground parts of plants, namely that in the case of the compounds daidzein, equol, estrone, and genistein, extreme values were recorded in plants grown on the control soil (variant 1). However, in the case of roots, the highest values were clearly recorded across all variants for the compound telmisartan, with the absolute highest result (616.94 ± 252.1 ng/g) for variant 8, the application of vermicompost of a mixture of 50% sewage sludge and 50% straw pellets. Overall, the highest average values are recorded in the case of the above-mentioned variants no. 1 (89.2 ± 38.18 ng/g) and variant no. 8 (61.34 ± 68.71 ng/g). This is followed by variant no. 2—compost based on 100% sludge with a value of 20.85 ± 7.39 ng/g, variant no. 7 (vermicompost based on 75% sludge and 25% pellets) with a value of 20.06 ± 25.80 ng/g, and variant no. 13 (pre-composted vermicompost based on 75% sludge and 25% pellets) with a value of 19.03 ± 49.78 ng/g. The lowest average values were recorded for all fertilized variants based on 100% pellets: variant no. 6 (4.56 ± 13.37 ng/g), variant no. 11 (4.88 ± 9.54 ng/g), and variant no. 16 (7.12 ± 3.48 ng/g).

3.3.3. Influence of Fertilization Variants on the Content of Micropollutants in Above-Ground Biomass

Extreme values were measured in plants from the control soil for the PPCPs daidzein (98.2 ± 22.12 ng/g), genistein (20.81 ± 1.81 ng/g), caffeine (14.09 ± 19.92 ng/g), and paraxanthine (9.42 ± 3.15 ng/g) as illustrated in Table 6. The compounds daidzein and genistein were measured only in biomass growing on the control soil (variant 1). The effect of fertilization with increased PPCP values was evident in variant 4 (compost generated from 50% sludge plus 50% pellets) with average values of 2.01 ± 4.39 ng/g dry matter, and in variant 15 (pre-composted vermicompost based on 25% sludge plus 75% pellets) with average values of 1.30 ± 4.27 ng/g dry matter, mainly due to the higher amount of caffeine and paraxanthine. The lowest average values were measured in variant no. 16—pre-composted vermicompost based on 100% pellets (0.04 ± 0.11 ng/g dry matter).

3.4. Results of Phytoremediation Indicators

The phytoremediation potential of cannabis plants is shown in Table 8. All values were calculated from the averages for individual PPCPS.

Table 8. Evaluation of phytoremediation indicators (TC = transfer coefficient, TF = translocation factor, and PPI = plant contamination index for individual PPCPs; NA = not available).

Compound	TC	TF	PPI
Caffeine	1.64	0.64	0.11
Carbamzepine	9.99	0.23	NA
Cetirizine	0.00	0.00	NA
Daidzein	79.2	0.04	0.00
Diclofenac	1.81	NA	2.62
Equol	282	0.00	0.73
Estron	883	0.00	0.00
Genistein	771	0.01	0.00
Lamotrigine	0.00	NA	NA
Paraxanthine	19.3	0.24	0.16
Telmisartan	116	0.00	182
Tramadol	0.18	2.03	NA
Triclosan	6.42	0.00	NA
Venlafaxine	NA	0.00	NA

The phytoremediation potential of cannabis plants based on the TC was demonstrated for the PPCPs caffeine, carbamazepine, diclofenac, equol, paraxanthine, telmisartan, and triclosan. The TF demonstrated increased accumulation in the above-ground parts of plants only for tramadol. The plant contamination index was manifested in the highest values for telmisartan, and then in noticeably lower values for diclofenac, equol, and paraxanthine.

4. Discussion

The application of composts and vermicomposts derived from sewage sludge influenced the uptake of pharmaceuticals and personal care products (PPCPs) in hemp (*Cannabis sativa* L.). Our results demonstrate that certain PPCPs, such as carbamazepine, cetirizine, lamotrigine, and telmisartan, accumulated in soil and roots following amendment, while above-ground biomass contained fewer contaminants, suggesting restricted translocation.

These findings align with previous studies indicating that soil amendments can modify contaminant bioavailability and uptake by plants [21]. Similarly, research on other crops, including spinach, has shown preferential accumulation of pharmaceuticals in roots rather than above-ground biomass [22].

Unlike prior studies that suggest that composting and vermicomposting can degrade certain PPCPs [10,11], our findings indicate that these processes do not universally eliminate PPCPs, particularly for persistent compounds such as telmisartan and carbamazepine. This discrepancy highlights the need to assess PPCP degradation efficiency under specific composting conditions. Additionally, the observed reduced bioavailability of some PPCPs in amended soils supports the hypothesis that organic matter can bind certain PPCPSs, limiting their plant uptake [23].

Our study also revealed that telmisartan exhibited the highest retention in roots, a pattern similar to that reported in prior work on PPCPs in spinach [22]. However, tramadol was the only PPCP displaying significant translocation to above-ground biomass, indicating compound-specific mobility differences. These findings underscore the role of plant defense mechanisms in restricting contaminant movement, which is consistent with research on the phytoremediation potential of hemp [12].

Additional studies on soil amendments further reinforce our observations. Research on humic acid-based cation buffers suggests that organic amendments can enhance nutrient availability while influencing contaminant behavior in soils [24]. Similarly, microbial interactions, such as those involving Pseudomonas fluorescens, have been shown to influence soil chemistry and plant nutrient uptake, which may have implications for PPCP mobility in hemp [25]. These findings suggest that microbial communities and organic matter composition in soil amendments could play an essential role in determining the bioavailability and translocation of PPCPs in plants.

Furthermore, previous studies highlighted the role of soil pH, organic matter content, and microbial activity in PPCP degradation and uptake [26]. The influence of these factors suggests that optimizing soil conditions could mitigate the accumulation of contaminants in crops. For instance, studies on the phytoremediation potential of other plant species, such as maize and sunflower, demonstrated higher translocation factors compared to hemp [27]. This indicates that while hemp exhibits some ability to sequester PPCPs, alternative crops may provide more efficient remediation strategies.

Despite these insights, our study suggests that hemp may not be an ideal candidate for PPCP phytoremediation due to its limited PPCP translocation. Future research should explore alternative crop species and enhanced composting techniques to mitigate PPCP contamination in agricultural systems. Expanding studies to different plant species and soil types could further refine our understanding of PPCPs mobility and uptake patterns.

5. Conclusions

This study examined the impact of composts and vermicomposts derived from sewage sludge and straw pellets on the accumulation of PPCPs. The findings demonstrate that while these amendments influenced the presence of certain PPCPs in soil and plant roots, the translocation to above-ground biomass was generally restricted. This suggests that cannabis plants may employ a defense mechanism that limits contaminant movement, particularly to protect generative organs from contamination.

A significant accumulation of contaminants was observed in plant roots, with carbamazepine and telmisartan showing the highest concentrations. In contrast, tramadol was one of the few PPCPs detected in elevated levels in above-ground biomass. These results indicate that while cannabis can absorb PPCPs from soil, its ability to transfer them to harvestable plant parts remains limited. Consequently, hemp may not be the most effective crop for remediating soils contaminated with pharmaceuticals and endocrine disruptors.

Given the variability in the data and observed fluctuations in PPCP concentration, further research is required to expand the dataset and assess additional plant species with potentially greater phytoremediation capabilities. Understanding the interactions between soil amendments, microbial activity, and plant physiology will be crucial for optimizing sustainable agricultural practices and identifying crops that offer both ecological benefits and commercial viability while minimizing the risk of PPCPs transfer into the food chain.

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