

Article

Uptake Pathways, Translocation, and Accumulation of Phthalate Esters in Tea Seedlings Under Hydroponic Conditions

Jie Li ^{1,†} , Shanjie Han ^{2,†}, Qiaolei Cai ¹, Xuchen Zhang ¹, Chuning Xu ¹, Zhengfan Yang ¹, Baoyu Han ¹ and Mengxin Wang ^{1,*} 

¹ College of Life Sciences, China Jiliang University, Hangzhou 310018, China; 821012410010@caas.cn (J.L.); s25090710002@cjl.u.edu.cn (Q.C.); 2200906107@cjl.u.edu.cn (X.Z.); 2200905104@cjl.u.edu.cn (C.X.); 2200906106@cjl.u.edu.cn (Z.Y.); hanbaoyu@cjl.u.edu.cn (B.H.)

² College of Quality and Standardization, China Jiliang University, Hangzhou 310018, China; hanshanjie@cjl.u.edu.cn

* Correspondence: wmx@cjl.u.edu.cn

† These authors contributed equally to this work.

Abstract

Phthalate esters (PAEs) are ubiquitously emerging pollutants in the environment and have a notably high detection rate in tea; they can leach out during consumption and pose potential risks to human health. However, the process of PAEs entering and accumulating in tea plants is undocumented. This study investigated the uptake of PAEs in tea plant seedlings, focusing on both root and foliar pathways under hydroponic conditions. In controlled indoor deposition experiments, PAEs on fresh tea leaves underwent rapid degradation within five days, with the degradation rates ranging from 66.98% to 81.69%; outdoor rates exhibited even higher degradation rates. This degradation process followed first-order kinetics. The results revealed that tea plants were capable of absorbing and translocating PAEs via roots and leaves, culminating in their accumulation in various tea plant tissues. The Root Concentration Factor (RCF) was highest for di(2-ethylhexyl) phthalate (DEHP). Conversely, the shoot concentration factor, Leaf Concentration Factor, and Translocation Factors for the leaves, stems, and roots for the PAEs were inversely related to the RCF. The moderated mediation analysis suggested that root concentration was strongly influenced by translocation-mediated pathways. However, leaf concentration was largely not mediated by the translocation pathways. These findings indicate that both root uptake and foliar deposition can contribute to PAE accumulation in tea plants, providing a basis for source apportionment and for designing targeted control strategies to reduce PAE contamination in tea production systems.

Keywords: root uptake; foliar deposition; hydroponic exposure; physicochemical properties; concentration factor; tea contamination



Academic Editor: Daniele Del Buono

Received: 1 January 2026

Revised: 25 March 2026

Accepted: 30 March 2026

Published: 1 April 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Recent studies have detected phthalate esters (PAEs) in almost all tea samples, indicating that they are common contaminants in tea [1–5]. PAEs present in tea can leach out during the brewing process [6], posing potential harm to consumers. PAEs belong to a class of endocrine-disrupting chemicals, and prolonged human exposure to PAEs increases the risk of deformities [7] and carcinogenesis [8]. Several countries and organizations, including China, the United States, Japan, and the European Union, have listed various PAEs, such as DEHP and DnBP, as priority restricted pollutants [9]. Given the

widespread consumption of tea and the hazard potential of PAEs, understanding how tea plants interact with these pollutants becomes crucial. However, the sources of phthalate contamination in tea leaves and whether tea trees can actively absorb PAEs are not yet clear. Some studies have suggested that machines or oils used in the tea processing steps of spreading, fixing, and rolling might contain PAEs, leading to contamination [2,3]; during the cultivation process, long-term agricultural activities and atmospheric deposition can increase the residues of DEHP, DBP, and other PAEs in tea gardens [4,5,10]. Furthermore, there is growing concern regarding organic pollution in agricultural soils. The average content of PAEs in agricultural soils ranges from a few $\mu\text{g}/\text{kg}$ to tens of mg/kg , with the total content exceeding $100 \text{ mg}/\text{kg}$ [11]. PAEs constitute a principal component of this agricultural soil pollution [12]. The concentrations of PAEs in Chinese tea plantation soils range from $0.002 \text{ mg}/\text{kg}$ to $10.90 \text{ mg}/\text{kg}$, posing potential ecological and health risks [13]. PAEs are ubiquitously found in the soils of tea plantations, thereby posing a potential risk of contamination to tea plants during their growth cycle. Therefore, understanding the origin of PAEs in the tea planting process is essential for reducing garden pollution and lowering the risk of leaf contamination. Through their root systems and foliage, plants are capable of taking up and accumulating organic compounds [14]. Tea plants can also absorb and transport polycyclic aromatic hydrocarbons through these two pathways [15]. Furthermore, PAEs can enter plants primarily through two pathways, the root system and the foliage, subsequently being translocated to other parts of the plant [16,17]. Research indicates that various plants, including cabbage [18], Ziyoucai [19], and wheat [20], can absorb and accumulate PAEs through both roots and leaves. Uptake pathways are influenced by the physicochemical properties of pollutants, environmental conditions for plant growth, and physiological differences among plant species [21,22]. Existing research indicates that the absorption of organic substances by plants is closely related to their properties, such as Log-Kow, and this absorption process can be effectively modeled and predicted utilizing neural network algorithms [22]. Wang et al. [23] have found that the PAE content in tea plants is related to environmental factors such as temperature, air quality, and precipitation; Li et al. [24] observed that different species and cultivars also exhibit varying capacities to absorb and accumulate PAEs. Therefore, studying the absorption, accumulation, transport, and dissolution of PAEs in tea plants through leaves and roots is crucial for understanding the sources of PAE contamination in tea gardens and formulating preventive measures.

Therefore, this study used tea seedlings under hydroponic conditions to test the hypothesis that PAEs can enter tea plants through both roots and leaves, but that their accumulation and translocation differ among compounds according to their physicochemical properties. Specifically, the objectives were to (1) investigate the natural dissipation of PAEs on fresh tea leaves; (2) compare root and foliar uptake pathways and characterize tissue-specific accumulation and translocation of PAEs in tea seedlings; (3) analyze the relationships between physicochemical properties and PAE behavior in tea plants; and (4) assess the indirect effects of PAE physicochemical properties on bioaccumulation and translocation using a moderated mediation framework.

2. Materials and Methods

2.1. Reagents and Materials

Dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), di-n-butyl phthalate (DBP), and bis(2-ethylhexyl) phthalate (DEHP) were acquired from Dr. Ehrenstorfer GmbH Company (Augsburg, BY, Germany) with a purity of 99.4%. The chromatographic-grade reagents n-hexane, anhydrous sodium sulfate, toluene, acetonitrile, anhydrous sodium chloride, ethyl acetate, and methanol were purchased from Tedia

Co., Inc. (Fairfield, OH, USA). Solid phase extraction (SPE) glass columns (CARB/NH₂, 1000 mg/6 mL) were purchased from Dikma Technologies Inc. (Beijing, China).

2.2. Plant Cultivation and Exposure Experiments

In this study, the Longjing 43 variety, a widely cultivated tea plant, was selected. Tea seeds were obtained from high-quality tea gardens in the West Lake area. Uniformly sized and plump tea seeds were selected, disinfected, soaked for germination, and then sown in a growth medium. The tea seedlings were grown until lignification and then transplanted into a hydroponic environment. Experimental conditions for hydroponic experiments were optimized based on previous descriptions [25]. To ensure the integrity of the tea seedling roots, they were rinsed with pure water and cleaned with a soft brush to remove substrate adhering to the roots. The seedlings were transferred to glass beakers for 10 days, and covered with aluminum foil to protect the roots from light. Pure water and different concentrations of nutrient solution (Table S1) were successively used for cultivation, gradually increasing to 100% concentration within 10 days to acclimate the seedlings to the hydroponic environment. The pH of the nutrient solution was adjusted to 5 with 0.1 mol/L NaOH or 0.1 mol/L H₂SO₄.

The plants were grown in a greenhouse in Hangzhou, Zhejiang Province, China, under controlled environmental conditions (PPFD = 300 $\mu\text{mol}/\text{m}^2/\text{s}$, light: dark cycle = 16 h:8 h, relative humidity 60~70%). The greenhouse air was connected to the external environment. After acclimating to the hydroponic environment, the plants were subjected to different treatments: nutrient solution containing PAEs (0.1 mg/L, 0.5 mg/L, 1.0 mg/L), nutrient solution without PAEs but with simulated PAE deposition reagent at different concentrations (0.1 mg/L, 0.5 mg/L, 1.0 mg/L) (Figure S1). Exposure concentrations (0.1–1.0 mg/L) were selected based on previous PAE plant uptake studies. Field data show that PAE levels in heavily contaminated water can reach 0.1–0.3 mg/L; thus, 0.1 mg/L represents a highly polluted environmental scenario. Meanwhile, 1.0 mg/L was included as an elevated mechanistic level to better compare uptake and translocation behaviors among PAEs [13,26–29].

Additionally, controls were set up: (a) control without added PAEs in the nutrient solution, (b) control without PAEs in the nutrient solution and without PAEs in the simulated deposition reagent to monitor potential contamination. To increase the solubility of PAEs in water, methanol was added to the nutrient solution (v:v = 0.05%) [30]. In addition, a control group was established that was treated with nutrient solution plus 0.05% methanol but without PAEs, in order to monitor plant growth.

Samples were collected at 0, 1, 3, 5, 7, 10, 14, 21, and 30 days after treatments. Tea plants were washed with deionized water and methanol, and cleaned plants were separated into roots, stems, and leaves. Plant tissues were wrapped in aluminum foil to ensure the separation of the samples, frozen in liquid nitrogen, ground with a mortar, and then processed for extraction.

2.3. Extraction of PAEs from Fresh Tea Leaves

To ascertain the concentration of PAEs, the analytical procedure was conducted on plant tissue samples, adhering to the methodology outlined in our prior research [23]. Specifically, a 2.00 g sample of finely ground tea plant tissue (accurate to 0.1 mg) was placed into a 50 mL polytetrafluoroethylene centrifuge tube, followed by the addition of 2.00 g of anhydrous sodium chloride and 20 mL of hexane. The mixture was then uniformly agitated using a vortex mixer. Subsequently, the sample underwent ultrasonic extraction at 40 °C for 30 min and was maintained in a 40 °C water bath for 12 h. Post-extraction, the sample was centrifuged at 4 °C and 3000 rpm for 2 min to separate the supernatant,

which was then collected. The residual sediment was treated with an additional 20 mL of hexane and centrifuged under identical conditions for 2 min, a process repeated twice. The collected supernatants from all three iterations were combined and evaporated under reduced pressure at 40 °C until nearly dry. This residue was then reconstituted with 8 mL of an acetonitrile–toluene mixture (3:1, *v/v*), preparing it for subsequent SPE processing.

The SPE column was preconditioned using 10 mL of an acetonitrile–toluene solution (3:1, *v/v*), and the initial effluent was discarded. Subsequently, the sample extract was introduced into the SPE column, collecting the effluent at a controlled flow rate of approximately 1 mL/min. Following this, 22 mL of the acetonitrile–toluene mixture was added to the column. The effluents from both these stages were combined and then subjected to evaporation under reduced pressure at 40 °C until nearly dry. After cooling, the residue was reconstituted with 1 mL of hexane, thoroughly mixed, and then filtered through a 0.22 µm membrane filter. This prepared sample was subsequently analyzed using Gas Chromatography–Mass Spectrometry (GC-MS) (Agilent Technologies, Wilmington, DE, USA).

2.4. GC-MS Analysis

The quantitative assessment of PAEs was conducted utilizing the Agilent 6890GC-5975B MSD system (Agilent Technologies, Wilmington, DE, USA). Chromatographic separation was achieved using an HP-5MS quartz capillary column, measuring 30 m in length, 250 µm in internal diameter, and with a film thickness of 0.25 µm. The GC oven temperature protocol commenced at 60 °C, which was sustained for 1 min, then was followed by ramping up to 220 °C at a rate of 20 °C/min, maintaining this temperature for another minute. The temperature was then further increased to 290 °C at a rate of 5 °C/min and held steady for 5 min. A 1 µL aliquot of the sample was introduced into the GC-MS system in a splitless injection mode, with the injector set at 280 °C. Helium, with a purity of 99.999%, served as the carrier gas. The ion source operated at a temperature of 230 °C, employing an ionization energy of 70 electron volts (eV). Analyses were performed in the Selected Ion Monitoring (SIM) mode.

2.5. Quality Assurance and Quality Control

To reduce contamination during the experimental process, contact with plastics was minimized throughout the entire experiment, including the steps of tea plant cultivation, sample extraction, transfer, and storage. Samples and extraction liquids were stored in aluminum foil and glass tubes, respectively. With the exception of leaf samples used in the simulated sedimentation experiment, all samples were surface-washed with GC-grade solvents after collection and prior to extraction to ensure that phthalates adsorbed on the surfaces of roots and stems were not included in the extracts. Glass enclosures were used to prevent air contamination during PAE spraying. All glassware and polytetrafluoroethylene (PTFE) tubes used in the experiment were soaked in a potassium permanganate-concentrated sulfuric acid solution before use, rinsed with deionized water, and then dried at 140 °C for at least two hours. Anhydrous sodium sulfate and anhydrous sodium chloride were heated in a muffle furnace at 400 °C for 4 h before the experiment. Each batch of samples included a set of procedural blanks and solvent blanks to monitor potential background contamination. The PAE content detected in the control group was used as the background value and subtracted from the treatment groups, and the PAE concentration in procedural blanks and solvent blanks was below the method's limit of detection.

2.6. Method Validation

Method validation was carried out using linearity, accuracy, precision, detection limit (LOD), quantification limit (LOQ), and standard recovery (Table S2). The linearity was obtained at $R^2 > 0.99$ for PAEs ranging from 1 to 1000 µg/L, except for DBP (500

µg/L). LOD and LOQ were calculated based on 3 times and 10 times the signal-to-noise ratio (S/N), respectively, for 30 measurements. The LODs for the five PAEs ranged from 0.2 to 0.6 µg/kg, while the LOQs ranged from 0.7 to 2.0 µg/kg. The recovery rates for the five PAEs ranged from 81.71 to 98.68%. The relative standard deviations at the three concentration levels were 4.0%~8.6%, indicating good precision of the method.

2.7. Statistical Data Analysis

The absorption and translocation of PAEs in tea plant seedlings are represented by the bioconcentration factor (BCF) and Translocation Factor (TF).

$$RCF = C_{\text{root}}/C_{\text{solution}} \quad (1)$$

$$SCF = C_{\text{stem}}/C_{\text{solution}} \quad (2)$$

$$LCF = C_{\text{leaf}}/C_{\text{solution}} \quad (3)$$

$$TF_{\text{leaf}} = C_{\text{leaf}}/C_{\text{root}} \quad (4)$$

$$TF_{\text{stem}} = C_{\text{stem}}/C_{\text{root}} \quad (5)$$

$$TF_{\text{stem1}} = C_{\text{stem1}}/C_{\text{leaf1}} \quad (6)$$

$$TF_{\text{root1}} = C_{\text{root1}}/C_{\text{leaf1}} \quad (7)$$

$$\text{Dissipation rate} = (C_i - C_f)/C_0 \times 100\% \quad (8)$$

In these formulaic representations, Root Concentration Factor (RCF), Stem Concentration Factor (SCF), and Leaf Concentration Factor (LCF) correspond to the enrichment factors of PAEs in the roots, stems, and leaves of the tea plant, respectively. The Translocation Factor (TF) quantifies the degree of PAE movement between two specific parts of the tea plant, such as Root-to-Stem Translocation Factor (TF_{stem}), Root-to-Leaf Translocation Factor (TF_{leaf}), and Leaf-to-Stem Translocation Factor (TF_{stem1}), under the simulated PAE deposition reagent treatment. C_{solution} denotes the PAE concentration in the solution used for the root treatment group, while C_{leaf} , C_{stem} , and C_{root} represent the concentrations of PAEs in the leaves, stems, and roots of the tea plant, respectively. C_{leaf1} , C_{stem1} , and C_{root1} represent the concentrations of PAEs in the leaves, stems, and roots of the tea plant under the simulated PAE deposition reagent treatment. The concentration in the solution is measured in mg/L, and in the tea plant tissues, it is measured in mg/kg (fresh weight). Elevated BCF and TF values signify enhanced absorption and translocation capabilities of the tea plants for PAEs. C_0 indicates the concentration of the solution sprayed in the simulated deposition experiment, C_i is the concentration of PAEs in the leaves on the i -th day post-treatment, and C_f refers to the PAEs concentration in the leaves of the control group during the simulated deposition experiment.

The moderated mediation analysis model followed a standard two-step structure:

$$M = aX + e_1 \quad (9)$$

$$Y = c'X + bM + b_{\text{int}}(M \times W) + e_2 \quad (10)$$

In this model, X: physicochemical predictor (e.g., log Kow, boiling point); M: mediator (Translocation Factor); Y: outcome (enrichment factor: RCF, SCF, or LCF); a, b: coefficients for $X \rightarrow M$ and $M \rightarrow Y$; int_b: coefficient for interaction term $M \times \text{Treatment}$; ab: indirect effect estimate ($a \times b$); ab_CI [2.5%], ab_CI [97.5%]: bootstrap confidence interval; ab_sig: Boolean indicator of whether the indirect effect is significant (based on CI); sobel_p: p -value from Sobel test.

The dissipation kinetics of PAEs on leaf surfaces were modeled according to first-order kinetics. The degradation rate constant (k) and half-life ($t_{1/2}$) were calculated using the following equations:

$$C_t = C_0 \cdot e^{-kt} \quad (11)$$

$$t_{1/2} = \ln(2)/k \quad (12)$$

In these equations, C_t : concentration of the compound at time t (mg/kg); C_0 : initial concentration at time zero; k : first-order degradation rate constant (typically in day^{-1} or hour^{-1}); t : time (in the same unit as used for k); $t_{1/2}$: half-life of the compound, representing the time required for its concentration to decrease by 50%.

All results are expressed as the mean $\pm$ variance ($n = 3$). Statistical analyses and graph creation were performed using R version 4.2.3 (Pearson's correlation analysis, heatmaps, and line charts) and Python version 3.3.1 (mediation analysis and dynamic model fitting).

3. Results and Discussion

3.1. Dissipation of PAEs on Fresh Tea Leaves

From the simulated deposition experiments with three different concentration treatments, the degradation dynamics of PAEs on tea seedling leaves are illustrated in Figure 1, and the dissipation parameters of PAEs are presented in Table 1. PAEs on fresh tea leaves rapidly dissipated within 7 days, followed by a relatively stable trend. The final content of the five PAEs on fresh tea leaves, from the highest to the lowest, was DMP > DEHP > DIBP > DBP > DEP. Groups M1, M2, and M3 all conformed to a first-order kinetic equation ($R^2 > 0.6$) (Figure 2). The final dissipation rates (α , day = 30) ranged from 66.98% to 81.69%. The final dissipation rates of PAEs on fresh tea leaves under three different treatments showed no significant differences (Table S3). However, under low-concentration treatments, the half-life of PAEs was greater than that under high-concentration treatments. The efficiency with which microbial enzymes degrade hydrophobic organic compounds is contingent on their capacity to migrate from the solid or hydrophobic phase into the aqueous phase, where microbial enzymes can access them [31]. The process is limited by low water solubility. In summary, at low concentrations, a greater proportion of PAEs remains tightly bound to the wax or cuticle on leaf surfaces. This results in low bioavailability and, consequently, a slower degradation process.

Among treatments at the same concentration, DEHP exhibited the highest persistence with the most extended half-life, succeeded by DIBP, DBP, DEP, and DMP in descending order. The dissipation rate of PAEs on fresh tea leaves, along with the degradation rates of various PAEs, might be influenced by environmental factors, biological dilution during the tea tree growth process, and the physicochemical properties of the compounds. The longer persistence of DEHP likely reflects stronger partitioning into the leaf cuticular waxes due to its higher hydrophobicity and lower water solubility, which may reduce desorption and dissipation from the leaf surface under indoor conditions. The results indicated that DEHP was more likely to be retained on the fresh tea leaves.

Research indicates that in Chinese cabbage, PAEs accumulate within the leaves, predominantly localizing on the wax layer covering the leaf surface [16]. The waxy layer on fresh tea leaves is primarily composed of long-chain fatty acids and their derivatives [32]. Therefore, PAEs with strong lipophilicity (or poor water solubility), such as DEHP, may be more prone to adsorption onto the waxy layer of the leaves. It should be noted that a stable indoor environment may result in an excessive preservation rate of PAEs, and further experiments should be conducted in more realistic environmental conditions. PAEs on field leaves exhibited higher dissipation rates, possibly influenced by UV radiation [33]. PAEs were degraded by 70% to 90% under intense UV exposure within only 300 min [34].

Elevated temperatures also accelerated PAE volatilization, causing differences in the dissipation rates based on the vapor pressure and boiling point of the compounds.

Table 1. Kinetic parameters for degradation of PAEs in fresh tea leaves under different initial concentrations.

PAE	C ₀ (mg/L)	k (d ^{−1})	t _{1/2} (d)	R ²	α (%)
DMP	0.1	0.105	6.622	0.819	81.698
	0.5	0.157	4.413	0.633	76.314
	1	0.218	3.18	0.757	79.749
DEP	0.1	0.072	9.63	0.771	76.372
	0.5	0.143	4.85	0.634	76.234
	1	0.189	3.67	0.74	78.781
DBP	0.1	0.062	11.138	0.901	75.817
	0.5	0.122	5.679	0.682	73.655
	1	0.148	4.688	0.74	77.275
DEHP	0.1	0.045	15.244	0.938	66.981
	0.5	0.094	7.371	0.78	71.21
	1	0.113	6.108	0.76	75.001
DIBP	0.1	0.058	12.041	0.865	74.087
	0.5	0.116	5.958	0.66	74.52
	1	0.156	4.448	0.739	77.594

Note: C₀: the initial concentration; k: the first-order degradation rate constant; t_{1/2}: the half-life; R²: the coefficient of determination of the kinetic model; α indicates the degradation percentage at the end of the experiment.

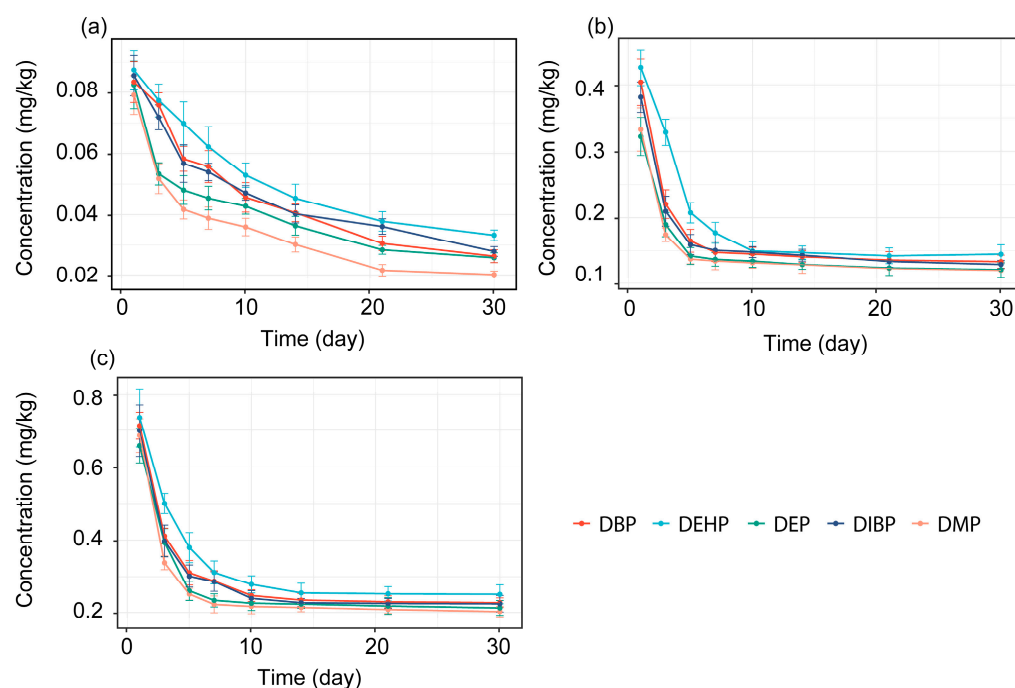


Figure 1. Degradation curves of PAEs in tea plants (via leaves). (a) treatment concentration of 0.1 mg/L; (b) treatment concentration of 0.5 mg/L; (c) treatment concentration of 1.0 mg/L. Dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), di-n-butyl phthalate (DBP), and bis(2-ethylhexyl) phthalate (DEHP).

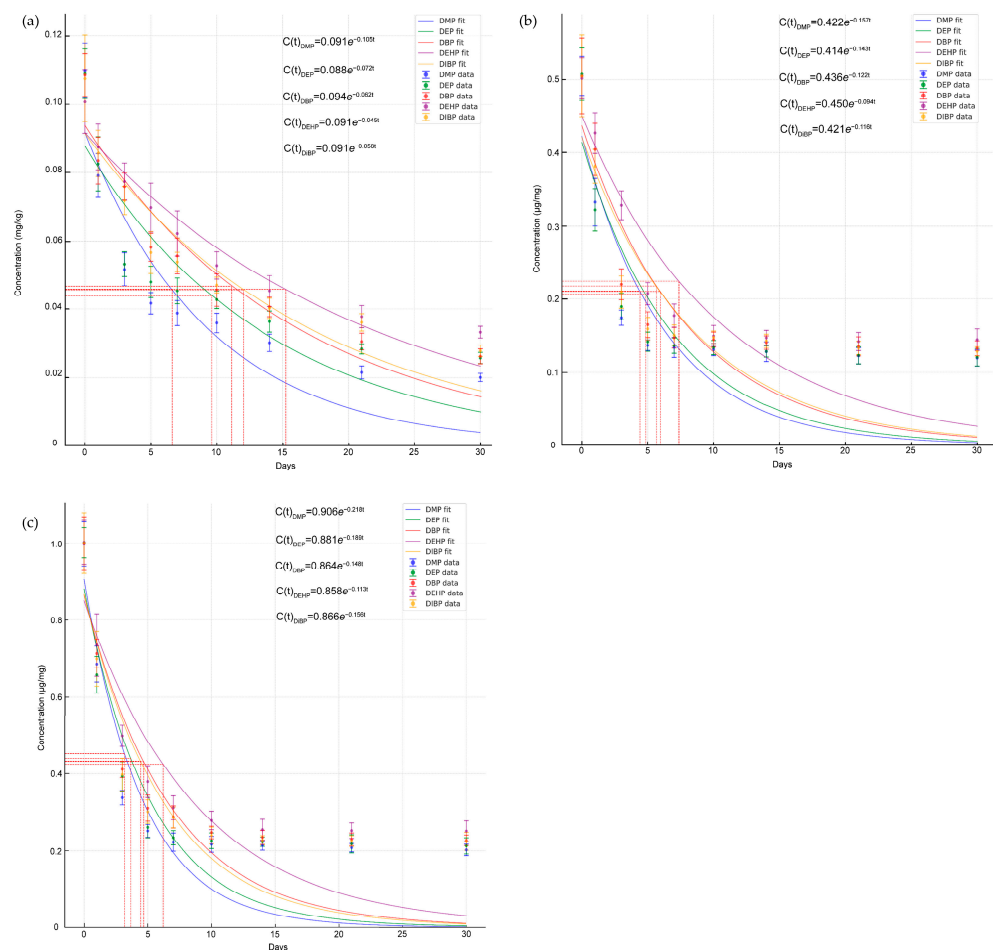


Figure 2. Fitting curves for the degradation half-life of PAEs in fresh tea leaves with a treatment concentration of 0.1 mg/L (a), 0.5 mg/L (b), and 1.0 mg/L (c). The figure presents various colored curves representing the predicted trajectories derived through half-life fitting, with dots marking actual data points, and the error bars positioned above and below each data point denoting the standard deviation of the data. A red dashed line originates from the half-life point on each predicted curve, extending vertically to intersect the x-axis at the corresponding day and horizontally to intersect the y-axis at the corresponding concentration level. Dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), di-n-butyl phthalate (DBP), and bis(2-ethylhexyl) phthalate (DEHP).

3.2. Uptake and Accumulation of PAEs in Tea Plant

In the control group, PAEs were not detected in tea roots, stems, or leaves, indicating no environmental or inter-group pollution during tea seedling cultivation, exposure experiments, and simulated deposition experiments. However, all treatment groups showed detectable levels of PAEs in tea plant tissues. Figure 3 depicts the dynamic changes in five PAEs within the roots, stems, and leaves of tea seedlings, as absorbed through their roots. The concentration (PAE content/sample fresh weight) in tea plant tissues increased with the treatment concentration, indicating a positive correlation between PAE absorption and the concentration in the nutrient solution. Significant concentration differences between the nutrient solution and plants accelerated PAE absorption. Within 7–10 days of exposure, the concentrations of PAEs in various tissues of tea seedlings rapidly increased and peaked. The highest PAE concentration in roots was 8.72–62.73 times that in stems, and the highest concentration in stems was 12.28–27.19 times that in leaves, suggesting that PAE absorption in tea seedlings is primarily concentrated in the roots. Similar absorption curves were observed for the same tissues at different exposure concentrations, with the

peak concentration occurring earlier in the roots (7 days) than in the stems and leaves (10 days). This phenomenon may be attributed to the plant's characteristics of absorbing organic compounds through the roots and transporting them upward. After reaching the peak, a decrease in PAE concentration was observed.

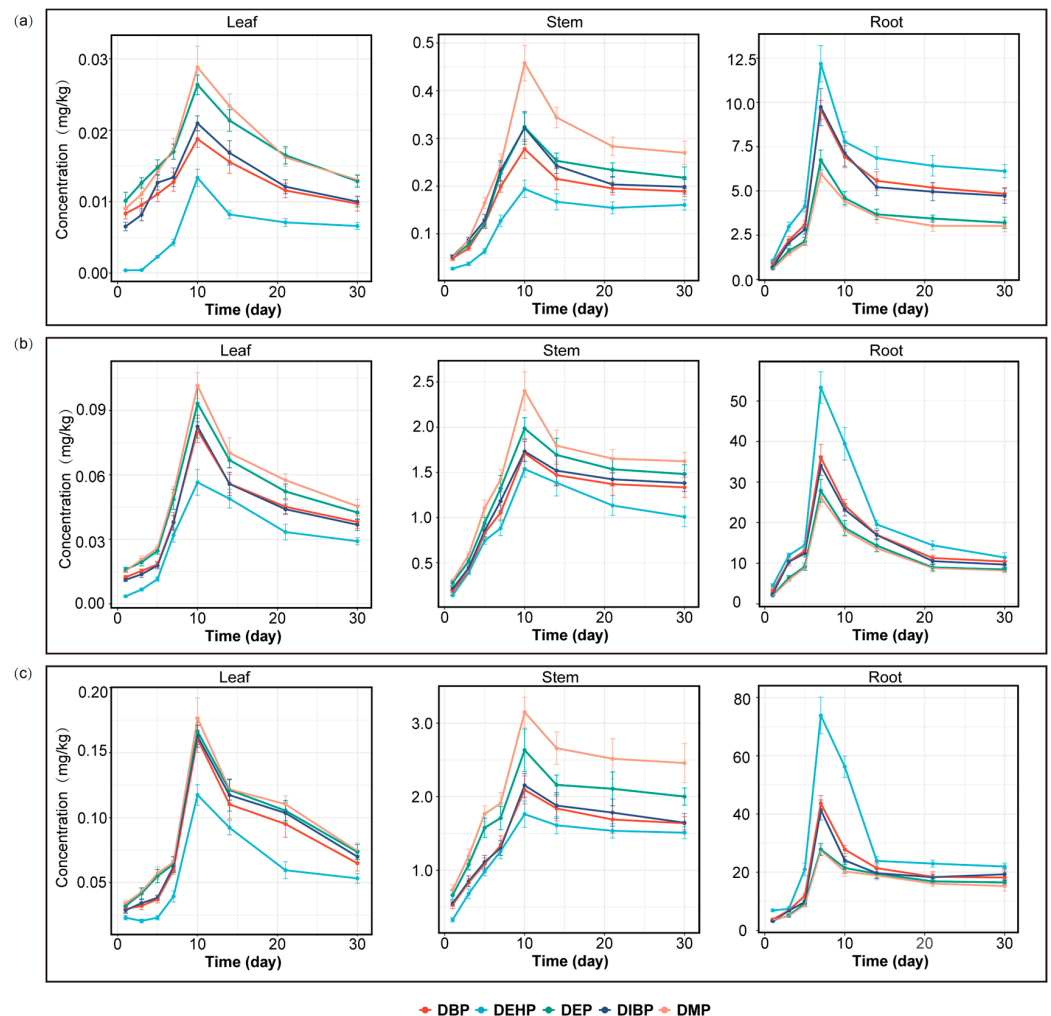


Figure 3. Uptake curves of PAEs in tea plants (via roots). (a) treatment concentration of 0.1 mg/L; (b) treatment concentration of 0.5 mg/L; (c) treatment concentration of 1.0 mg/L. Dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), di-n-butyl phthalate (DBP), and bis(2-ethylhexyl) phthalate (DEHP).

For tea seedlings in simulated deposition experiments, the dynamic changes in the concentrations of five PAEs in roots and stems are shown in Figure 4. Similar to the dynamics of absorption through the roots, the PAE content in tissues rapidly increased, reaching its peak within 5 days of exposure. Additionally, the maximum values of PAEs in roots and stems were much lower than those in tea seedlings treated through the roots. This difference may be related to the distribution of PAEs on fresh tea leaves. On the 30th day of exposure, the accumulation and translocation of PAEs in tea seedlings were investigated. To assess the differences in the accumulation and translocation of the five PAEs in tea seedlings more comprehensively, the RCF, SCF, LCF, TF_{leaf} , TF_{stem} , TF_{stem1} , and TF_{root1} were analyzed (Figure 5).

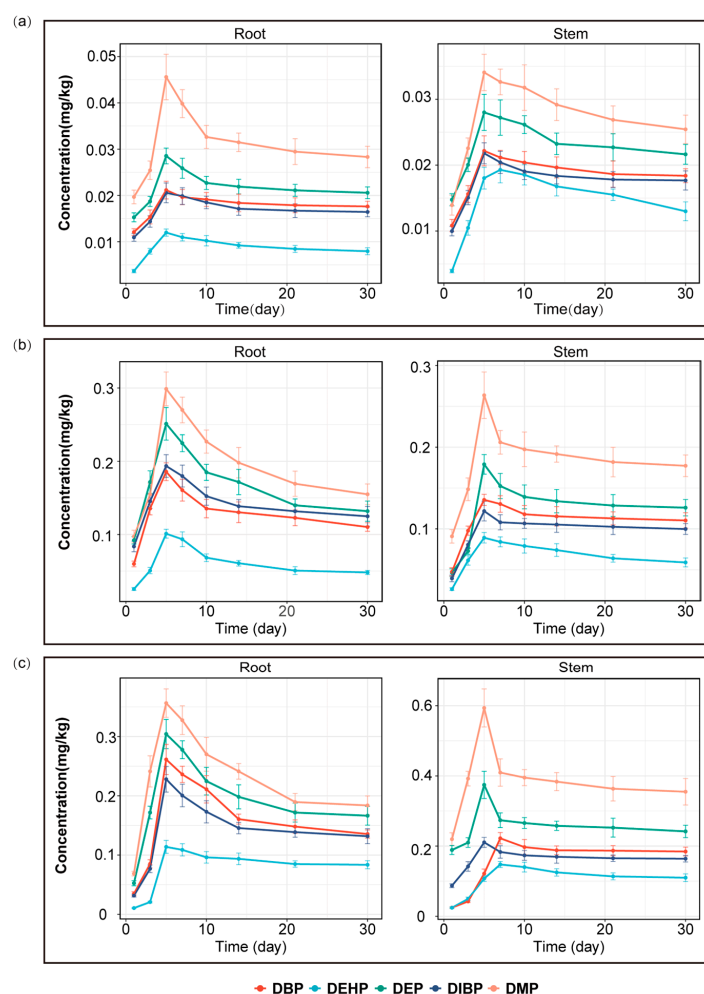


Figure 4. Uptake curves of PAEs in tea plants (via leaves): (a) treatment concentration of 0.1 mg/L; (b) treatment concentration of 0.5 mg/L; (c) treatment concentration of 1.0 mg/L. Dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), di-n-butyl phthalate (DBP), and bis(2-ethylhexyl) phthalate (DEHP).

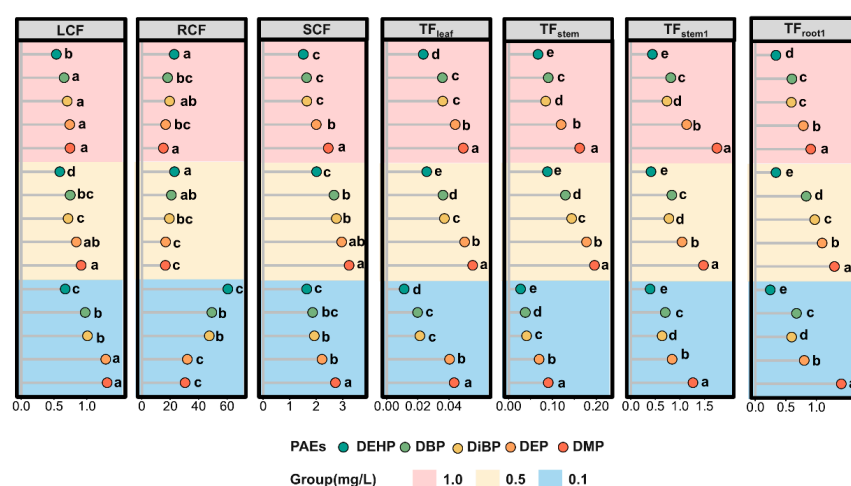


Figure 5. Accumulation and translocation coefficients of five PAE variants in tea plants. LCF, Leaf Concentration Factor; RCF, Root Concentration Factor; SCF, Stem Concentration Factor; TF_{leaf} , Root-to-Leaf Translocation Factor; TF_{stem} , Root-to-Stem Translocation Factor; TF_{stem1} , Leaf-to-Stem Translocation Factor; TF_{root1} , Leaf-to-Root Translocation Factor. The five colored dots correspond to

five PAEs, and three colored blocks correspond to three different treatment concentrations. Different letters represent significant differences. Dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DiBP), di-n-butyl phthalate (DBP), and bis(2-ethylhexyl) phthalate (DEHP).

For the root treatment experiments, the average concentration order of PAEs with the three treatments in roots was DEHP > DBP > DIBP > DEP > DMP, while stems and leaves showed the opposite order. DEHP had the highest RCF, followed by DBP, DIBP, DEP, and DMP. However, the order of LCF and SCF was the opposite to that of RCF. DEHP was more prone to accumulation in roots, while DMP tended to accumulate mainly in stems and leaves. Furthermore, all five PAEs exhibited the order RCF > SCF > LCF ($p < 0.05$), indicating that their concentrations were the highest in the roots, followed by stems and leaves during exposure. The TF_{stem} values for all five PAEs were less than 1, suggesting limited capability for movement from roots to stems in tea seedlings; the TF_{leaf} values were all less than 0.1, suggesting limited capability for movement from roots to leaves. Regarding leaf treatment, only TF_{stem1} and TF_{root1} for tea seedlings were analyzed. Within the roots and stems, the mean concentration order of various PAEs in the three treatment groups was DMP > DEP > DBP > DIBP > DEHP. In the leaf treatment experiments, TF_{stem1} and TF_{root1} for DMP were the highest, succeeded by DEP, DBP, DIBP, and DEHP. This opposite ranking indicates a partitioning trade-off, in which more hydrophobic PAEs were preferentially retained in roots, whereas less hydrophobic compounds were more efficiently mobilized to stems and leaves. The results indicated that in leaf absorption, DEHP tended to accumulate mainly in the roots and stems of tea seedlings. The accumulation and translocation behaviors of PAEs in the roots and leaves were similar. Furthermore, the hydroponic system facilitated the comparison of root uptake and foliar deposition under controlled conditions, but it did not fully reproduce PAE exposure in tea plantations. This study should be regarded as a controlled mechanistic study rather than a reproduction of PAE behavior under actual tea garden conditions.

The PAE absorption behavior of tea plants is similar to that of the absorption of polycyclic aromatic hydrocarbons in plants [35] and to the absorption pattern of anthraquinone in tea plants [36]. This phenomenon may be due to the biodegradation or growth dilution of PAEs by tea plants. Compared with foliar deposition, hydroponic root exposure provides continuous contact with dissolved PAEs, whereas foliar-applied PAEs are first subject to surface retention, dissipation, and cuticular sequestration before only a small fraction can enter internal tissues and move downward. For cabbage, over 85.0% of PAEs enriched in leaves were concentrated in the waxy layer [16], while the content in the leaf flesh was relatively low. Most PAEs on leaves were either degraded or captured by the waxy layer, allowing only a small amount of PAEs to enter the leaves and migrate downward. Different plants may exhibit different absorption behaviors towards PAEs. Similarly, in a study on two leafy vegetables, Li et al. [19] found that six PAEs were more likely to accumulate in roots, opposite to the accumulation pattern in the stems and branches. However, Zhang et al. [37] found that in *Zizania latifolia*, the concentrations of DBP, BBP, and DEHP were the highest in stems, followed by the roots and leaves. Compared to previous studies on RCFs and TFs, it can be inferred that the ability of tea seedlings to absorb PAEs from roots is similar to that of Gaogengbai and Ziyoucai [19] and six leafy vegetables [38], but stronger than that of Alfalfa [39] and *Zizania latifolia* [37]. Such variability could be attributable to factors like the type of plant species, the conditions of growth, the setup of experiments, and the individual physicochemical characteristics of each PAE.

3.3. Correlation Analysis Between the Behavior of PAEs in Tea Plants and Their Physicochemical Properties

In this research, tea seedlings absorbed all five PAEs, yet there was notable variability in the accumulation and translocation behaviors of each individual PAE compound. In the foliage, the concentration of these PAEs was observed in descending order: DMP > DEP > DIBP > DBP > DEHP. Conversely, the concentration sequence in the roots and stems was the reverse of this order. This opposite ranking between underground and aboveground tissues suggests a partitioning trade-off: more hydrophobic PAEs were preferentially retained in root tissues, whereas less hydrophobic compounds were more efficiently mobilized to stems and leaves.

The correlation analysis between the physicochemical properties of various PAEs and RCF, SCF, LCF, TFs, and half-life was conducted (Figure 6). For PAEs, their log Kow value showed a positive correlation with RCF ($r = 0.962$, $p = 0.009$) while showing a negative correlation with SCF ($r = -0.864$, $p = 0.059$) and LCF ($r = -0.978$, $p = 0.004$). This suggested that the lipophilicity of pollutants affects the absorption of pollutants by tea plants. The log Kow value of PAEs was negatively correlated with TF_{stem} ($r = -0.893$, $p = 0.041$), TF_{leaf} ($r = -0.993$, $p = 0.001$), TF_{stem1} ($r = -0.901$, $p = 0.037$), and TF_{root1} ($r = -0.988$, $p = 0.002$). The results indicated that as hydrophobicity increased, PAEs were more likely to migrate upwards and downwards in tea plants. RCF was negatively correlated with the vapor pressure of PAEs, positively correlated with the boiling point, and negatively correlated with water solubility. In contrast, SCF, LCF, and TFs showed the opposite patterns to those of RCF.

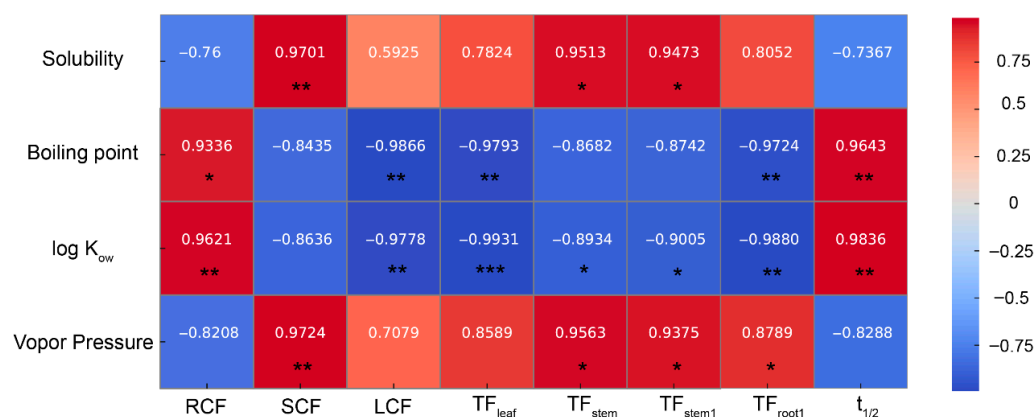


Figure 6. The correlation analysis of the accumulation and Translocation Factors with the physicochemical properties of PAEs. RCF, SCF, LCF, TF_{stem} , TF_{leaf} , TF_{stem1} , TF_{root1} , and half-life ($t_{1/2}$) and physicochemical properties (solubility, boiling point, octanol-water partition coefficient, and vapor pressure) of PAEs are shown. The correlation and its statistical significance are articulated through the correlation coefficient values (p -values), with the intensity of color in graphical representations indicative of the correlation's strength. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

PAEs that exhibit greater lipophilicity tend to be more strongly retained within the roots and stems, in contrast to those with lower lipophilicity, which are predominantly translocated through the xylem and phloem [40]. Some studies have indicated that highly hydrophilic and polar organic compounds tend to be more easily transported [41], consistent with the results of this study. Li et al. [26] observed that the log Kow of PAEs inversely correlated with log TF_{leaf} of Gaogengbai and Ziyoucai. However, Qiu et al. [42] revealed that the uptake behavior of organochlorine and organophosphorus pesticides was not simply linearly related to log Kow. The findings from these studies indicated a relationship involving the log Kow of organic compounds, and the accumulation and translocation patterns within plants was not universally applicable among different plant species.

3.4. Moderated Mediation Analysis

In this study, a moderated mediation analysis was conducted to assess the indirect effects of physicochemical properties of PAEs on the bioaccumulation and translocation behaviors in tea seedlings. Specifically, TFs were considered mediators in the pathway from physicochemical properties of PAEs to their corresponding enrichment factors (RCF, SCF, and LCF). Treatment concentrations were introduced as a moderator to explore how they influence the mediated effects of PAEs on accumulation in different plant tissues.

Figure 7 illustrated the results of the moderated mediation analysis, showing that all six physicochemical properties significantly influenced RCF and SCF through the Translocation Factors TF_{stem} and TF_{leaf} . In contrast, only solubility and vapor pressure exhibited significantly moderated mediation effects on LCF via the Translocation Factor TF_{leaf} .

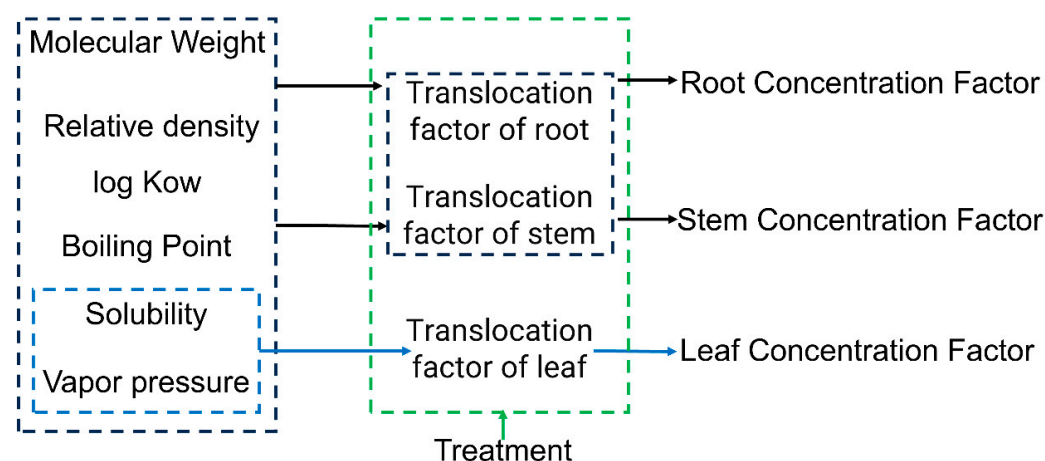


Figure 7. Conceptual framework of the moderated mediation model for pollutant translocation and accumulation in tea plant tissues. Dashed boxes represent variable groupings: black for all six physicochemical properties, blue for volatile or water-soluble properties, and green for the three translocation (transporter) factors. Black and blue arrows represent the mediation pathways from physicochemical properties to the corresponding enrichment factors, as grouped within the same color-coded dashed boxes. Together, they form complete mediation effect pathways. Green arrows indicate that treatment concentration moderates the model by influencing the Translocation Factors.

For the Root Concentration Factor (RCF), all moderated mediation pathways involving Translocation Factors were statistically significant (Figure 8 and Table S4). For example, the $\log Kow \rightarrow TF_{leaf} \rightarrow RCF$ pathway yielded a significant indirect effect ($a \times b = 6.42$, $p < 0.001$). At the lowest treatment concentration (0.1 mg/L), a one-unit increase in TF_{leaf} was associated with a large decrease in RCF (slope = -1241), whereas at the highest concentration (1.0 mg/L), this negative effect was less pronounced (slope = -672 ; interaction $p < 0.001$). The $\log Kow \rightarrow TF_{stem} \rightarrow RCF$ pathway showed a similar pattern ($a \times b = 4.16$, $p < 0.001$), with the TF_{stem} effect on the RCF shifting from -256 at 0.1 mg/L to 66.8 at 1.0 mg/L, indicating a reversal from inhibitory to facilitatory mediation at high exposure. This trend was observed consistently for all chemical descriptors; for instance, high vapor pressure exhibited an especially strong negative indirect impact on RCF via TF_{leaf} ($a \times b = -9409$, $p < 0.001$), whereas properties such as molecular weight and boiling point showed smaller yet significant mediated effects ($a \times b \approx 0.2\text{--}0.4$, $p < 0.001$) (Table S5). Overall, these results indicated that root concentration was strongly influenced by translocation-mediated pathways, and that the mediator's impact diminishes or even reverses at higher contaminant levels. Increased concentrations may weaken or even alter the mediating effect of transport on root accumulation, suggesting that distribution rearrangement or near-saturation may occur under high exposure conditions.

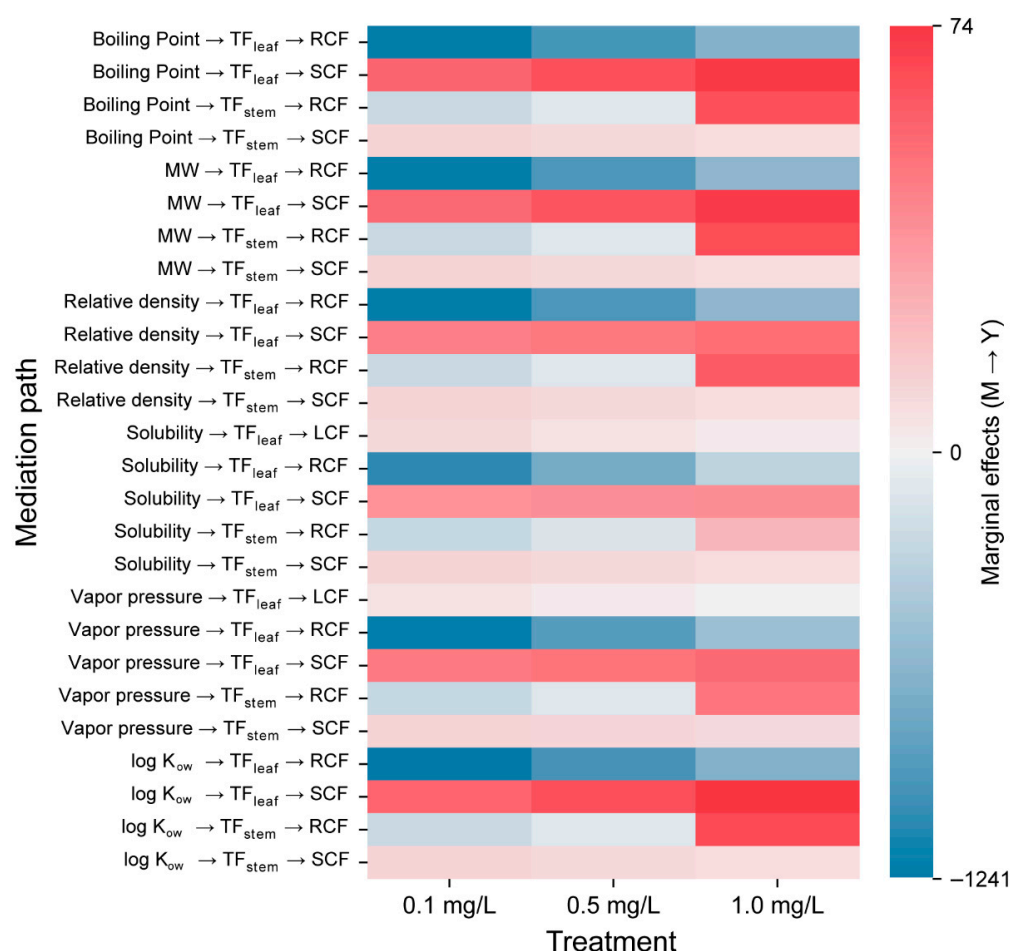


Figure 8. Heatmap of moderated marginal effects for translocation pathways under different treatment concentrations. This heatmap illustrates the marginal effects of Translocation Factors (TF_{leaf} or TF_{stem}) on bioaccumulation outcomes (RCF, SCF, or LCF) across three treatment concentrations (0.1, 0.5, and 1.0 mg/L). Color intensity reflects the direction and magnitude of the marginal effect, with blue indicating negative effects and red indicating positive effects. Stronger red or blue color highlights the positive or negative direction in which the treatment significantly alters the strength of the indirect effect by modulating transfer efficiency.

In contrast to RCF, the moderated mediation pathways for SCF showed no significant dependence on treatment concentration (interaction $p > 0.1$ for all cases). Nevertheless, all the chemical properties examined still exhibited significant indirect effects on SCF via the Translocation Factors ($p < 0.001$) (Figure 8 and Table S4). For example, in the $\log K_{ow} \rightarrow TF_{leaf} \rightarrow SCF$ pathway, TF_{leaf} had a positive influence on SCF that increased slightly from 56.2 at 0.1 mg/L to 74.1 at 1.0 mg/L, although this change was not statistically significant (interaction $p = 0.15$). Because $\log K_{ow}$ was negatively related to TF_{leaf} , the overall indirect effect of $\log K_{ow}$ via TF_{leaf} on SCF was negative ($a \times b = -0.270$, $p < 0.001$). Similarly, other properties' effects via TF_{leaf} were positive and largely invariant with concentration (e.g., for vapor pressure, the $TF_{leaf} \rightarrow SCF$ slope rose from 55.9 at 0.1 mg/L to 73.1 at 1.0 mg/L; $a \times b = 348.7$, $p < 0.001$). Mediation via TF_{stem} was also significant for all properties (e.g., $\log K_{ow} \rightarrow TF_{stem} \rightarrow SCF$: $a \times b = -0.171$, $p < 0.001$) (Table S5), but these indirect contributions were relatively small. The effect of TF_{stem} on SCF remained positive and showed only a slight decline at higher concentrations (for instance, 11.7 at 0.1 mg/L vs. 8.1 at 1.0 mg/L for $\log K_{ow}$; interaction $p = 0.11$). Overall, the mediated effects on SCF were stable across the 0.1–1.0 mg/L range with no significant moderation, suggesting that the contribution of translocation to stem accumulation was largely constant within the

tested concentration range. The mediating effect observed in the stem is relatively stable, suggesting that the stem functions more as a transport pathway than as the most sensitive site of accumulation.

For the Leaf Concentration Factor (LCF), only one moderated mediation pathway was statistically significant (Figure 8 and Table S4). Specifically, solubility $\rightarrow$ $TF_{leaf} \rightarrow$ LCF showed a positive indirect effect of solubility on LCF ($a \times b = 1.0 \times 10^{-4}$, $p = 0.0036$) (Table S5). In this pathway, TF_{leaf} had a substantial positive effect on LCF at 0.1 mg/L (+9.37), which weakened to +2.53 at 1.0 mg/L; however, this attenuation with concentration was not significant (interaction $p = 0.17$). In addition, the path of regulating LCF via vapor pressure could be considered significant even though its ab sig was TRUE, although its p value was greater than 0.05. No other chemical property exhibited a significant indirect effect on LCF ($p > 0.05$), suggesting that leaf concentration was largely not mediated by the translocation pathways examined under varying treatment levels. Only a few pathways showed significant accumulation in the leaves, indicating that the leaves are not the primary site of accumulation and are more limited by transport efficiency.

4. Conclusions

This study demonstrated that tea seedlings can take up phthalate esters through both roots and leaves under controlled hydroponic conditions, supporting our hypothesis that these compounds can enter tea plants through multiple pathways and show compound-specific accumulation behaviors. Phthalate esters deposited on fresh leaves dissipated rapidly, especially under field conditions, indicating that leaf surface residues are relatively short-lived. In contrast, root exposure led to stronger internal accumulation than foliar exposure, showing that root uptake is an important pathway for phthalate entry into tea plants. The results further showed clear tissue-specific differences in the fate of individual compounds. More hydrophobic phthalates were preferentially retained in the roots, whereas less hydrophobic compounds were more readily translocated to the stems and leaves. This pattern indicates that physicochemical properties play a central role in controlling the balance between retention and long-distance transport in tea plants. The statistical analysis further suggested that root accumulation was strongly influenced by translocation-related processes and that this influence varied with exposure concentration, whereas stem accumulation was comparatively stable and leaf accumulation was only weakly mediated by the translocation pathways examined.

Overall, these findings indicate that phthalate contamination in fresh tea leaves may originate from both external deposition onto leaves and internal uptake from the root environment. Therefore, reducing phthalate contamination in tea production requires attention not only to atmospheric and surface deposition, but also to root-zone exposure from contaminated water, soil, and agricultural materials. These results provide a mechanistic basis for source identification and for the development of targeted strategies to reduce phthalate contamination and associated food safety risks in tea cultivation.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agriculture16070783/s1>: Table S1: The chemical composition of the tea seeding nutrient solution; Table S2: Method validation of linearity, recoveries, LOD, and LOQ for five PAEs in tea; Table S3: The results of the non-parametric tests between the groups of the final degradation rate α of the PAEs; Table S4: Marginal effects of treatment on significantly mediated translocation pathways; Table S5: Parameter estimates and significance tests for moderated mediation pathways from physicochemical predictors to bioaccumulation outcomes; Figure S1: Diagram of sample of laboratory facilities.

Author Contributions: Conceptualization, J.L., M.W., and B.H.; methodology, J.L., S.H., Q.C., X.Z., C.X., Z.Y., M.W., and B.H.; software, J.L.; validation, J.L.; formal analysis, J.L., M.W., and S.H.; writing—original draft preparation, J.L. and S.H.; writing—review and editing, M.W. and B.H.; project administration, M.W. and B.H.; funding acquisition, M.W. and B.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Zhejiang Provincial Natural Science Foundation of China (LMS25C160001), the National Natural Science Foundation of China (32402354 and 32072626), and the Project of Innovation and Entrepreneurship Training for National Undergraduates (202410356036).

Data Availability Statement: Data sharing not applicable.

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

References

1. Du, L.; Ma, L.; Qiao, Y.; Lu, Y.; Xiao, D. Determination of Phthalate Esters in Teas and Tea Infusions by Gas Chromatography–Mass Spectrometry. *Food Chem.* **2016**, *197*, 1200–1206. [[CrossRef](#)]
2. Liu, P.; Chen, H.; Gao, G.; Hao, Z.; Wang, C.; Ma, G.; Chai, Y.; Zhang, L.; Liu, X. Occurrence and Residue Pattern of Phthalate Esters in Fresh Tea Leaves and during Tea Manufacturing and Brewing. *J. Agric. Food Chem.* **2016**, *64*, 8909–8917. [[CrossRef](#)]
3. Tang, Y.; Wang, M.; Pan, C.; Mi, S.; Han, B. Determination of Five Phthalate Esters in Tea and Their Dynamic Characteristics during Black Tea Processing. *Foods* **2022**, *11*, 1266. [[CrossRef](#)]
4. Wang, M.; Han, S.; Wu, Y.; Tang, Y.; Li, J.; Pan, C.; Han, B. Spatiotemporal Dynamics of Phthalate Esters in Tea Plants Growing Different Geographical Environments and an Attempt on Their Risk Assessment. *J. Agric. Food Chem.* **2023**, *71*, 6434–6444. [[CrossRef](#)] [[PubMed](#)]
5. Li, J.; Han, S.; Xu, R.; Zhang, X.; Liang, J.; Wang, M.; Han, B. Insight into the Effect of Geographic Location and Intercropping on Contamination Characteristics and Exposure Risk of Phthalate Esters (PAEs) in Tea Plantation Soils. *J. Integr. Agric.* **2024**, *23*, 3896–3911. [[CrossRef](#)]
6. Carr Kinnear, E.J.; Miller, K.Y.; Tong, A.Z. Impacts of Brewing Time, Brewing Temperature and Brands on the Leaching of Phthalates and Bisphenol A in Dry Tea. *Food Addit. Contam. Part A* **2021**, *38*, 1755–1766. [[CrossRef](#)] [[PubMed](#)]
7. Wang, L.; Duan, W.; Zhao, Y.; Sun, G.; Lin, Y.; Gao, Y. The Exposure Levels of Phthalates in Pregnant Women and Impact Factors of Fetal Malformation. *Hum. Exp. Toxicol.* **2021**, *40*, S622–S631. [[CrossRef](#)]
8. National Toxicology Program (NTP). *NTP Technical Report on the Toxicology and Carcinogenesis Studies of Di(2-ethylhexyl) Phthalate (CASRN 117-81-7) Administered in Feed to Sprague Dawley (Hsd:Sprague Dawley® SD®) Rats*; National Toxicology Program: Research Triangle Park, NC, USA, 2021; p. 601.
9. Han, Z.; Xue, J.; Li, Y. Phthalate's Multiple Hormonal Effects and Their Supplementary Dietary Regulation Scheme of Health Risks for Children. *Environ. Sci. Pollut. Res.* **2022**, *29*, 29016–29032. [[CrossRef](#)]
10. Wang, X.; Zhang, Y.; Huang, B.; Chen, Z.; Zhong, M.; Wang, W.; Liu, X.; Fan, Y.N.; Hu, W. Atmospheric Phthalate Pollution in Plastic Agricultural Greenhouses in Shaanxi Province, China. *Environ. Pollut.* **2021**, *269*, 116096. [[CrossRef](#)] [[PubMed](#)]
11. Du, Q.; Chen, Q.; Chen, X.; Li, W.; Zhao, X.; Gao, W.; Tu, K.; Liu, Y. Concentration Distribution and Health Risk Assessment of Phthalate Esters (PAEs) in Various Environmental Media in China. *Environ. Sci.* **2025**, *46*, 2684–2693. [[CrossRef](#)]
12. Sun, J.; Pan, L.; Tsang, D.C.W.; Zhan, Y.; Zhu, L.; Li, X. Organic Contamination and Remediation in the Agricultural Soils of China: A Critical Review. *Sci. Total Environ.* **2018**, *615*, 724–740. [[CrossRef](#)]
13. Li, Y.; Wang, J.; Bai, H.; Ni, K.; Liu, K.; Lu, P. Occurrence, Sources, and Risk Assessments of Phthalic Acid Esters in Tea Plantations in China. *J. Environ. Chem. Eng.* **2022**, *10*, 107636. [[CrossRef](#)]
14. Feng, N.; Pan, B.; Huang, H.; Huang, Y.; Lyu, H.; Xiang, L.; Zhao, H.; Liu, B.; Li, Y.; Cai, Q.; et al. Uptake, Translocation, and Biotransformation of Phthalate Acid Esters in Crop Plants: A Comprehensive Review. *J. Hazard. Mater.* **2025**, *489*, 137580. [[CrossRef](#)] [[PubMed](#)]
15. Lin, D.; Zhu, L.; He, W.; Tu, Y. Tea Plant Uptake and Translocation of Polycyclic Aromatic Hydrocarbons from Water and around Air. *J. Agric. Food Chem.* **2006**, *54*, 3658–3662. [[CrossRef](#)]
16. Zeng, L.J.; Huang, Y.H.; Lü, H.; Geng, J.; Zhao, H.M.; Xiang, L.; Li, H.; Li, Y.W.; Mo, C.H.; Cai, Q.Y.; et al. Uptake Pathways of Phthalates (PAEs) into Chinese Flowering Cabbage Grown in Plastic Greenhouses and Lowering PAE Accumulation by Spraying PAE-Degrading Bacterial Strain. *Sci. Total Environ.* **2022**, *815*, 152854. [[CrossRef](#)] [[PubMed](#)]
17. Fan, Y.; Zeng, Y.; Huang, Y.; Guan, Y.F.; Sun, Y.; Chen, S.; Mai, B. Accumulation and Translocation of Traditional and Novel Organophosphate Esters and Phthalic Acid Esters in Plants during the Whole Life Cycle. *Chemosphere* **2022**, *307*, 135670. [[CrossRef](#)] [[PubMed](#)]

18. Cheng, Z.; Wang, Y.; Qiao, B.; Zhang, Q.; Sun, H. Insights into Mechanisms Involved in the Uptake, Translocation, and Metabolism of Phthalate Esters in Chinese Cabbage (*Brassica rapa* var. *chinensis*). *Sci. Total Environ.* **2021**, *768*, 144945. [\[CrossRef\]](#)
19. Li, Y.; Yan, H.; Liu, Q.; Li, X.; Ge, J.; Yu, X. Accumulation and Transport Patterns of Six Phthalic Acid Esters (PAEs) in Two Leafy Vegetables under Hydroponic Conditions. *Chemosphere* **2020**, *249*, 126457. [\[CrossRef\]](#)
20. Shi, M.; Sun, Y.; Wang, Z.; He, G.; Quan, H.; He, H. Plastic Film Mulching Increased the Accumulation and Human Health Risks of Phthalate Esters in Wheat Grains. *Environ. Pollut.* **2019**, *250*, 1–7. [\[CrossRef\]](#)
21. Fernandes, A.S.; Bragança, I.; Homem, V. Personal care products in soil-plant and hydroponic systems: Uptake, translocation, and accumulation. *Sci. Total Environ.* **2024**, *912*, 168894. [\[CrossRef\]](#)
22. Bagheri, M.; He, X.; Oustriere, N.; Liu, W.; Shi, H.; Limmer, M.A.; Burken, J.G. Investigating Plant Uptake of Organic Contaminants through Transpiration Stream Concentration Factor and Neural Network Models. *Sci. Total Environ.* **2021**, *751*, 141418. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Wang, M.; Tang, Y.; Mi, S.; Pan, J.; Guo, C.; Li, J.; Han, B. Difference in Accumulation of Five Phthalate Esters in Different Elite Tea Cultivars and Their Correlation with Environment Factors. *Agriculture* **2022**, *12*, 1516. [\[CrossRef\]](#)
24. Li, Y.W.; Cai, Q.Y.; Mo, C.H.; Zeng, Q.Y.; Lü, H.; Li, Q.S.; Xu, G.S. Plant Uptake and Enhanced Dissipation of Di(2-Ethylhexyl) Phthalate (DEHP) in Spiked Soils by Different Plant Species. *Int. J. Phytoremediat.* **2014**, *16*, 609–620. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Liang, Y.; Zhou, L.; Zhang, X.; Yu, H.; Guo, M.; Yu, J.; Wang, X.; Yang, M.; Lou, Z.; Luo, F.; et al. Uptake, Accumulation, Translocation, and Subcellular Distribution of Perchlorate in Tea (*Camellia sinensis* L.) Plants. *J. Agric. Food Chem.* **2021**, *69*, 4655–4662. [\[CrossRef\]](#)
26. Chang, H.; Ma, Y.; Jiang, J.; Yan, Y.; Tang, Z.; Mao, W.; Wang, G.; Dong, J.; Zhao, W.; Gao, X.; et al. Plasticizer Contamination in Irrigation Water: Residue Characteristics and Toxic Effects of DBP and DEHP on Wheat Growth and Metabolism. *Ecotoxicol. Environ. Saf.* **2025**, *301*, 118510. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Fan, Y.; Li, T.; Zhang, Z.; Song, X.; Cun, D.; Cui, B.; Wang, Y. Uptake, Accumulation, and Degradation of Dibutyl Phthalate by Three Wetland Plants. *Water Sci. Technol.* **2023**, *88*, 1508–1517. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Vannucchi, F.; Francini, A.; Pierattini, E.C.; Raffaelli, A.; Sebastiani, L. *Populus alba* dioctyl phthalate uptake from contaminated water. *Environ. Sci. Pollut. Res. Int.* **2019**, *26*, 25564–25572. [\[CrossRef\]](#)
29. Gholaminejad, A.; Mehdizadeh, G.; Dolatimehr, A.; Arfaeina, H.; Farjadfard, S.; Dobaradaran, S.; Bonyadi, Z.; Ramavandi, B. Phthalate Esters Pollution in the Leachate, Soil, and Water Around a Landfill Near The Sea, Iran. *Environ. Res.* **2024**, *248*, 118234. [\[CrossRef\]](#)
30. Lin, Q.; Yang, X.; Huang, X.; Wang, S.; Chao, Y.; Qiu, R. Subcellular Distribution and Uptake Mechanism of Di-n-Butyl Phthalate in Roots of Pumpkin (*Cucurbita moschata*) Seedlings. *Environ. Sci. Pollut. Res.* **2016**, *23*, 329–337. [\[CrossRef\]](#)
31. Zhu, S.; Li, M.; Qian, T.; Chen, J.; Pan, T. Influence of Surfactants on Interfacial Microbial Degradation of Hydrophobic Organic Compounds. *Catalysts* **2025**, *15*, 187. [\[CrossRef\]](#)
32. Zhu, X.; Zhang, Y.; Du, Z.; Chen, X.; Zhou, X.; Kong, X.; Sun, W.; Chen, Z.; Chen, C.; Chen, M. Tender Leaf and Fully-Expanded Leaf Exhibited Distinct Cuticle Structure and Wax Lipid Composition in *Camellia sinensis* cv Fuyun 6. *Sci. Rep.* **2018**, *8*, 14944. [\[CrossRef\]](#)
33. Barreca, S.; Indelicato, R.; Orecchio, S.; Pace, A. Photodegradation of Selected Phthalates on Mural Painting Surfaces under UV Light Irradiation. *Microchem. J.* **2014**, *114*, 192–196. [\[CrossRef\]](#)
34. Wang, C.; Zeng, T.; Gu, C.; Zhu, S.; Zhang, Q.; Luo, X. Photodegradation Pathways of Typical Phthalic Acid Esters Under UV, UV/TiO₂, and UV-Vis/Bi₂WO₆ Systems. *Front. Chem.* **2019**, *7*, 852. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Zhao, C.; Xu, J.; Shang, D.; Zhang, Y.; Zhang, J.; Xie, H.; Kong, Q.; Wang, Q. Application of Constructed Wetlands in the PAH Remediation of Surface Water: A Review. *Sci. Total Environ.* **2021**, *780*, 146605. [\[CrossRef\]](#)
36. Yang, M.; Luo, F.; Zhang, X.; Wang, X.; Sun, H.; Lou, Z.; Zhou, L.; Chen, Z. Uptake, Translocation, and Metabolism of Anthracene in Tea Plants. *Sci. Total Environ.* **2022**, *821*, 152905. [\[CrossRef\]](#)
37. Zhang, D.; Zhou, K.; Liu, C.; Li, X.; Pan, S.; Zhong, L. Dissipation, Uptake, Translocation and Accumulation of Five Phthalic Acid Esters in Sediment-Zizania latifolia System. *Chemosphere* **2023**, *315*, 137651. [\[CrossRef\]](#)
38. Li, Y.; Yan, H.; Yu, X. Uptake and Accumulation of Di-n-Butyl Phthalate in Six Leafy Vegetables under Hydroponic Conditions. *Food Prod. Process. Nutr.* **2019**, *1*, 9. [\[CrossRef\]](#)
39. Ren, W.; Wang, Y.; Huang, Y.; Liu, F.; Teng, Y. Uptake, Translocation and Metabolism of Di-n-Butyl Phthalate in Alfalfa (*Medicago sativa*). *Sci. Total Environ.* **2020**, *731*, 138974. [\[CrossRef\]](#)
40. Liu, Q.; Wang, X.; Yang, R.; Yang, L.; Sun, B.; Zhu, L. Uptake Kinetics, Accumulation, and Long-Distance Transport of Organophosphate Esters in Plants: Impacts of Chemical and Plant Properties. *Environ. Sci. Technol.* **2019**, *53*, 4940–4947. [\[CrossRef\]](#)

41. Ju, C.; Dong, S.; Zhang, H.; Yao, S.; Wang, F.; Cao, D.; Xu, S.; Fang, H.; Yu, Y. Subcellular Distribution Governing Accumulation and Translocation of Pesticides in Wheat (*Triticum aestivum* L.). *Chemosphere* **2020**, *248*, 126024. [[CrossRef](#)] [[PubMed](#)]
42. Qiu, J.; Chen, G.; Xu, J.; Luo, E.; Liu, Y.; Wang, F.; Zhou, H.; Liu, Y.; Zhu, F.; Ouyang, G. In Vivo Tracing of Organochloride and Organophosphorus Pesticides in Different Organs of Hydroponically Grown Malabar Spinach (*Basella alba* L.). *J. Hazard. Mater.* **2016**, *316*, 52–59. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.