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Transport via xylem of trichloroethylene in wheat, corn, and tomato seedlings

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ABSTRACT

Transport via xylem of trichloroethylene (TCE) from roots to shoots in seedlings of wheat, corn, and tomato was measured following a 24-h exposure of plant roots to hydroponic solutions containing TCE. Dewdrops on plant leaves were also collected to test the foliar uptake by plants and the volatilization of TCE from shoot to air. Results indicated that the TCE concentration in xylem sap of wheat and corn decreased significantly with increasing TCE concentration in external solutions, where the initial concentration was set at 10–30 mg l^{-1}. The translocation stream concentration factor (TSCF) with the three plant species, defined as the ratio of the contaminant concentration in plant xylem sap to that in external solution, decreased sharply with increasing external TCE concentration or with increasing exposure time. Among the three plant species tested, the efficiency of TCE transport from roots to shoots followed the order of corn > wheat > tomato, based on the TCE concentration in xylem sap and the TSCF value. However, the TCE removal efficiency from external solution by three plant species followed the order of wheat > corn > tomato, because of the strong exchange of TCE between corn leaves and air and the rapid movement downward via phloem inside the plant. TCE concentrations in dewdrops collected from wheat and corn were far higher than in the xylem sap, especially with the corn.

1. Introduction

Due to the wide pesticide application, irrigation with wastewater, sewage sludge disposal, waste discharge and accidental chemical release, many food crops are susceptible to contamination by various organic wastes [1–3]. The need to better understand the mechanism and influential factors of the contaminant uptake by plants and transport via plants has promoted active investigations on the plant-uptake process [4–10]. Analyses of the concentrations of nonionic organic contaminants in plant roots in relation to the external concentrations in water (or soil water) from extensive sources have revealed that these contaminants enter plants largely by passive process [4,10–12]. The process may be viewed to consist of a series of partitions between plant water and plant organic matter with various plant components [10]. Translocation of these chemicals to shoots from root uptake proceeds in the direction of decreasing chemical potential, which is considered to be more efficient for compounds of intermediate polarity ($1 \le \log K_{ow} \le 3$) [4]. For a chemical, the efficiency of translocation is described in terms of the transpiration stream concentration factor (TSCF), which is defined as the ratio of chemical concentration in transpiration stream to that in the external solution. The concentration in the transpiration stream is usually assessed indirectly from the mass of chemical accumulated in the shoots for a known volume of water transpired. The TSCF of a chemical is assumed to have a maximum of 1.0 for passive uptake [4,11] and to be independent of chemical concentration in the external solution when partition equilibrium between root organic component and water was reached. The accumulation by shoots is determined by the partitioning between xylem sap and adjacent stem [4,10,12]. Currently, models for the uptake and transport of chemicals in plants have been applied in pesticide manufacturing, risk assessment, and biotechnology [11]. However, direct evidence for the assumed chemical transport via xylem is much warranted to substantiate the assumed in-plant translocation process. Experimental tests on chemical transport via xylems are thus undertaken in this study.

Trichloroethylene (TCE) is used widely as a solvent to remove grease from metal parts and as an ingredient in adhesives, paint removers, and spot removers. TCE is very volatile and has a moderately high water solubility of 1100 mg l^{-1}. It has been widely detected in groundwater and surface waters as a result of manufacturing, use, and disposal of the chemical [13]. Previously, we studied the uptake of TCE by rice seedlings from nutrient solution with and without coexisting organic compounds [12,14]. Results from single-TCE experiments indicated that TCE concentrations in rice roots and shoots decreased with the TCE concentration in

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external solutions or the exposure time. There was no steady root concentration factor (RCF) and shoot concentration factor (SCF), significant difference with other compounds, such as atrazine, *o*-chlorophenol and 2,4-dichlorophenol [14], as well as Lindane [1], O-methylcarbamoyloximes, substituted phenylureas [4], and phenanthrene. Because of the high TCE volatility from plant leaves to air, the potential for reverse TCE vapor uptake by leaves could thus interfere with the net TCE transport into plant roots and the subsequent translocation into shoots.

In the present study, the dewdrops and xylem saps in wheat, corn and tomato exposed to different TCE concentrations were collected and analyzed for better understanding the uptake of TCE by plants and the translocation of TCE within plants.

2. Experimental

2.1. Preparation of plant seedlings

Seeds of wheat (*Triticum aestivum* L., cv Chunhua), corn (*Zea mays* L., cv kennian) and tomato (*Lycopersicon esculentum Miller*) were surface sterilized with 30% H_2O_2 for 10 min, rinsed and soaked in deionized water overnight, and then placed on a nylon net floating on a 0.5 mM $CaCl_2$ solution until germinated. Every six seedlings of each plant species were transferred to a 4-l container filled with a modified 1/5-strength Hoagland nutrient solution. The composition of the nutrient solution was: 1.0 mM KNO_3, 1.0 mM $Ca(NO_3)_2$, 0.5 mM $MgSO_4$, 0.1 mM KH_2PO_4, 1.0 μM $MnCl_2$, 3 μM H_3BO_3, 1 μM $(NH_4)_6Mo_7O_{24}$, 1 μM $ZnSO_4$, 0.2 μM $CuSO_4$ and 60 μM Fe(III)-ethylenediaminetetra-acetic acid (EDTA). The pH of the nutrient solution was adjusted to 6.0 using 0.1 M KOH or HCl solution. Plants were grown hydroponically for 1–3 wk before the experiments. The nutrient solution was aerated continuously and renewed every two days. Uniform seedlings were selected and transplanted to brown glass bottles (a group of five wheat seedlings, one corn seedling or tomato seedling per bottle) containing 600 ml of a nutrient solution just before experiment, bottles were wrapped with aluminized paper and the open areas between the cap and plant seedlings were sealed with sponge wrapped with aluminized paper.

2.2. Treatments with contaminants

Trichloroethylene used for plant-uptake studies was supplied by Sigma–Aldrich Company. The experiments were carried out in a controlled environment with a 14 h light period (260–350 $\mu mol\, m^{-2}\, s^{-1}$) at temperatures of 25 °C day and 20 °C night. The relative humidity was 70%. In experiment 1, the wheat seedlings were exposed to nutrient solutions with different TCE at 10, 20, 30 and 40 $mg\, l^{-1}$ for 22 h (2 h after the light period started), collecting the sap for 6 h, then collecting the xylem sap and final external solution. In experiment 2, 12 groups of wheat seedlings were exposed to nutrient solutions with the initial TCE concentration at 40 $mg\, l^{-1}$. At selected times (1, 2, 12, and 22 h), wheat seedlings in three replicated groups were cut off and the xylem sap and final external solution were collected. In experiment 3, the corn seedlings were exposed to nutrient solutions with different TCE at 0, 10, 20, 30 and 40 $mg\, l^{-1}$ for 22 h (2 h after the light period started), collecting the sap for 6 h, then collecting the xylem sap and final external solution. In experiment 4, 12 wheat seedlings were exposed to nutrient solutions with the initial TCE concentration at 40 $mg\, l^{-1}$. At selected times (1, 2, 4, 13, 18 and 24 h), three replicated corn seedlings were cut off and the xylem sap and final external solution were collected. In experiment 5, the tomato seedlings were exposed to nutrient solutions with different (initial) TCE at 1, 2, 3 and 8 $mg\, l^{-1}$, collecting the xylem sap and final external solution after 24 h. At the end of the each experiment, the plant seedlings were weighed after blotted dry with tissue paper.

2.3. Xylem sap collection and analyses of TCE concentrations

In each experiment, fronds of three replicate plants were cut at the base of the shoot (*c*. 1 cm above the roots). The cut surfaces were rinsed with deionized water and blotted dry. Xylem exudates were collected for 1 h after excision.

Xylem saps, dewdrops and final external solutions in each experiment were immediately extracted with n-hexane after being collected, and were analyzed for TCE by an Agilent 6890 gas chromatograph equipped with a ^{63}Ni electron capture detector (ECD) using a HP-5 capillary column (0.32 mm × 30 m × 0.25 μm) and a split injection mode. The recovery of the solution samples in this experiment was 95.8 ± 1.2% (n = 5). Measured values of samples were not corrected for the recovery.

3. Results and discussion

3.1. Transpiration efficiency of TCE in plants

Because of the short exposure (within 24 h) to a relatively low concentration of TCE (less than 4% of the solubility), no toxicity symptoms were observed in all of experiments. Average biomasses of plants in each experiment were listed in Table 1. There was no significant difference in the biomass with different exposed concentrations. About 100–300 μl of xylem exudates were collected from the wheat experiment (experiment 1), 50–100 μl collected from the corn experiment (experiment 3), and 100–300 μl collected from the tomato experiment (experiment 5).

TCE concentrations in xylem sap collected from wheat seedlings were 0.24 ± 0.07, 0.17 ± 0.03, 0.13 ± 0.01 and 0.39 ± 0.09 $mg\, l^{-1}$ when the initial TCE concentrations in nutrient solution were 10, 20, 30 and 40 $mg\, l^{-1}$; the respective final TCE concentrations in external solution were 0.40 ± 0.03, 0.57 ± 0.08, 1.61 ± 0.11 and 3.06 ± 0.10 $mg\, l^{-1}$ (Table 1). After a 22-h plant uptake, the TCE concentration in nutrient solution showed 96%, 97%, 95% and 92% reductions, respectively. The ratio of TCE concentration in xylem sap to that in final external solution (TSFC) in wheat seedling in the present study was not constant (Table 2); it decreased with increasing initial or final TCE concentration in final external solution, as has been found with rice seedlings [14]. These observations disagree with the hypothesis that the TSCF of a contaminant should be independent of its concentration in external solution [4]. This indicates that the uptake of TCE by plants roots could not be explained solely by a physical partition process nor predicted by models based only on passive uptake [4,5,7,10]. There was no significant difference in

Table 1
Biomasses (g fresh weight) of plant seedlings exposed to various concentrations of (TCE) in nutrient solution (mean ± S.E., n = 12–18).

Plant	Wheat		Corn		Tomato
	Experiment 1n = 12	Experiment 2n = 12	Experiment 3n = 12	Experiment 4n = 18	Experiment 5n = 12
Shoot	0.98 ± 0.02	0.99 ± 0.05	0.72 ± 0.04	0.79 ± 0.03	2.39 ± 0.41
Root	0.53 ± 0.02	0.58 ± 0.05	0.48 ± 0.04	0.35 ± 0.02	0.59 ± 0.09
Total	1.51 ± 0.03	1.58 ± 0.10	1.20 ± 0.06	1.14 ± 0.04	2.98 ± 0.48

Table 2
Xylem transport efficiency of TCE in wheat, corn and tomato seedlings (mean ± S.E., $n = 3$).

Plant	TCE concentration, mg l^{-1}					Significance level
Wheat	C_0^*	10	20	30	40	
	$C_{\text{xylem sap}}$	0.24 ± 0.07	0.17 ± 0.03	0.13 ± 0.01	0.39 ± 0.09	NS
	C_f^{**}	0.40 ± 0.03	0.57 ± 0.08	1.61 ± 0.11	3.06 ± 0.10	***
	TSCF***	0.59 ± 0.27	0.36 ± 0.15	0.085 ± 0.01	0.050 ± 0.02	*
Corn	C_0^*	10	20	30	40	
	$C_{\text{xylem sap}}$	1.39 ± 0.26	0.76 ± 0.25	0.57 ± 0.07	0.74 ± 0.04	*
	C_f^{**}	3.67 ± 0.28	4.35 ± 0.05	8.61 ± 0.60	13.14 ± 1.47	***
	TSCF**	0.38 ± 0.08	0.17 ± 0.06	0.067 ± 0.013	0.058 ± 0.009	***
Tomato	C_0^*	1	2	3	8	
	$C_{\text{xylem sap}}$	0.033 ± 0.009	0.022 ± 0.007	0.023 ± 0.002	0.078 ± 0.017	NS
	C_f^{**}	0.81 ± 0.16	1.03 ± 0.02	1.20 ± 0.21	1.20 ± 0.06	NS
	TSCF**	0.048 ± 0.017	0.022 ± 0.007	0.021 ± 0.006	0.067 ± 0.017	NS

C_0^*: Initial TCE concentration in nutrient solution (mg l^{-1}).
C_f^{**}: Final TCE concentration in nutrient solution (mg l^{-1}).
TSCF***: Ratios of TCE concentration in xylem sap to TCE concentration in final external solution (mg l^{-1}).
NS, not significant.
$^{**}P < 0.01$.
* $P < 0.05$.
*** $P < 0.001$.

the volume of the final external solution between TCE treatments, indicating that the effect of TCE uptake on plant transpiration rate was negligible, similar to the results in previous report [14].

Results of TCE uptake and transport by corn and tomato seedlings from nutrient solution in experiments 3 and 5 provided more evidence that the ratio of TCE concentration in xylem sap to TCE concentration in final external solution (TSCF) was not constant (Table 2). In experiment 3, the observed TSCF in corn seedlings decreased with increasing initial or final TCE concentration in external solution. The TSCF of TCE in tomato seedlings changed from 0.021 to 0.067 at initial and final TCE concentrations in external solution in experiment 5. Although exposed to the same initial TCE concentration, corn seedlings showed lower removal efficiency than wheat seedlings. In experiment 3, 63%, 78%, 71% and 67% of TCE were removed by corn seedlings when the initial TCE concentrations in nutrient solution were set at 10, 20, 30, 40 mg l^{-1}, respectively. The final TCE concentrations in experiment 3 were far more (by 4–9 times) than those in experiment 1. However, TCE concentrations in xylem sap with corn seedlings were 1.9–5.8 times more than those with wheat seedlings, resulting in the lower calculated TSCF values with corn seedlings than with wheat seedlings (Table 2). In the present study, TCE showed the least translocation from roots to shoots with tomato, and thus the calculated TSCF with tomato was far less than those with corn and wheat, even though the initial TCE concentrations in external solution with tomato were less than those in wheat and corn (Table 2).

3.2. Concentrations of TCE in dewdrops

Before harvest, dewdrops on plant leaves in experiments 1 and 3 were collected carefully at selected times (every 10–15 min), and extracted with hexane to determine the TCE concentration. About 60–300 μl and 10–50 μl of dewdrops were collected from corn and wheat leaves within 6 h, whereas the dewdrop from tomato seedlings could not be collected in this experiment. A series of 10-ml control solution were put into culture dishes 15 min in order to test the TCE dissolution from air into water during the experiment process (control 1).

Results showed that the TCE concentration in control solution was negligible, indicating that TCE in dewdrops were mainly contributed by volatilization via shoots along with water vapor. Results also indicated that TCE concentrations in dewdrops collected from wheat seedlings were 2–3 times higher than those in xylem sap when the initial TCE concentration were at 20–40 mg l^{-1} (Fig. 1) but were lower than that in xylem sap (Figs. 1 and 2) at a low initial TCE concentration in nutrient solution (10 mg l^{-1}). TCE concentrations in xylem sap and dewdrop collected from wheat seedlings in experiment 1 indicated the TCE transport from roots to shoots was higher than that from shoots to dewdrops.

Compared with wheat seedlings, corn seedlings showed a higher TCE transport efficiency from shoots to dewdrops (Fig. 3). TCE concentrations in dewdrops from corn leaves were far higher (by 2–8 times) than those in xylem sap, and increased with increasing TCE concentration in external solution (Fig. 3). Similar to a previous report that TCE in plant could be taken up via shoots from air (foliar uptake) and transported to roots [14], TCE was detected in the final external solutions of control treatments (control 2) in experiment 3 that were not contaminated with TCE before experiment. Meanwhile, TCE was also detected in the dewdrops collected from control 2 in experiment 3. The TCE concentrations in control dewdrops as a function of the foliar uptake time were shown in Fig. 4. Due to its high solubility (1100 mg l^{-1}) and volatility, TCE could be easily translocated via plant transpiration streams to plant shoots and volatilized along with water into air to give rise to higher TCE concentration in corn dewdrops (Figs. 2 and 3). On the other hand, the foliar uptake of TCE by shoots concurred with the TCE volatilization [13], and the downward transport via phloem decreased with increasing TCE concentration in roots or external solution. As a

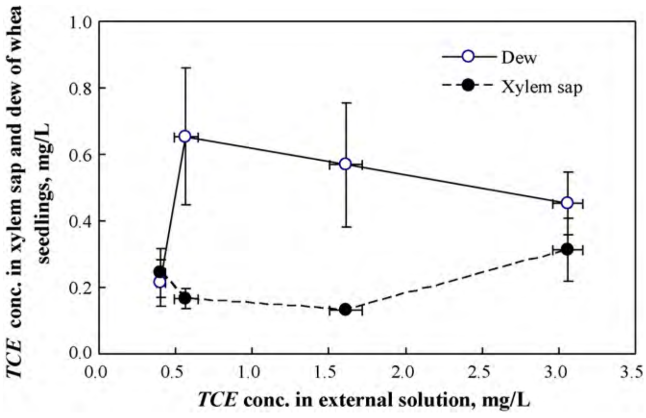

Fig. 1. Change of TCE concentration in dew and in xylem sap in wheat seedlings with TCE concentration in external solution. Each point is the mean of three replicates. Error bars represent S.E.

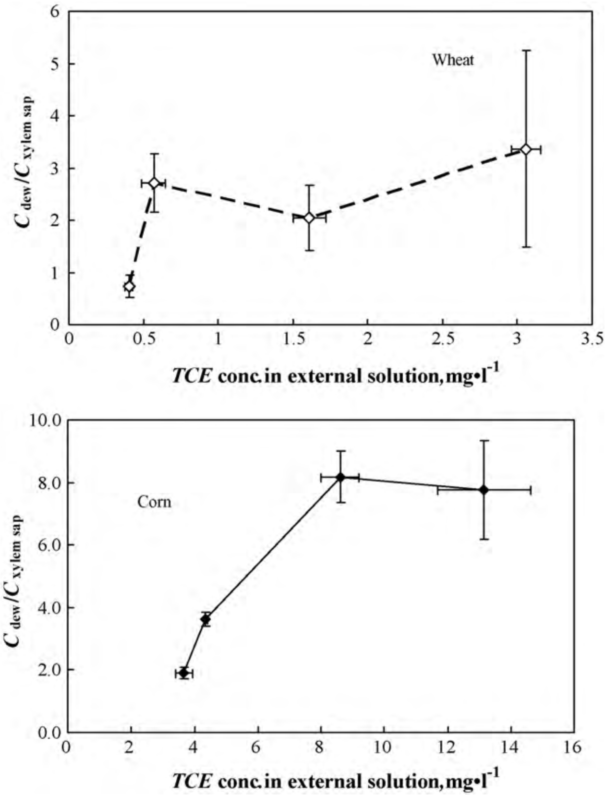

Fig. 2. Change in transport efficiency of TCE from wheat and corn seedlings to dewdrop with uptake time. Each point is the mean of three replicates. Error bars represent S.E.

result, the TSCF of TCE in plants decreased with increasing TCE concentration in external solution, and the TCE concentration in control dewdrops decreased sharply with an increase in uptake time after the fast initial foliar uptake of TCE. Compared with wheat seedlings, the stronger foliar uptake and downward movement via phloem with corn seedlings resulted in higher TCE concentrations in the final external solution (Table 2).

3.3. *Effect of exposure time on xylem transport efficiency*

Results from both experiments 2 and 4 indicated that the TCE concentration in xylem sap of wheat seedlings increased slowly with increasing exposure time within 2 h, and then decreased sharply with the exposure time. To wheat seedlings, the transport efficiency as represented by the ratio of TCE concentration in xylem sap to TCE concentration in external solution (TSCF) showed a sharp decrease (by 99%) after 2–22 h (Fig. 5). The trend of the TCE transport efficiency with the exposure time for corn seedlings was similar to that in wheat seedlings, which showed a 97% reduction of TSCF after 2–24 h (Fig. 6).

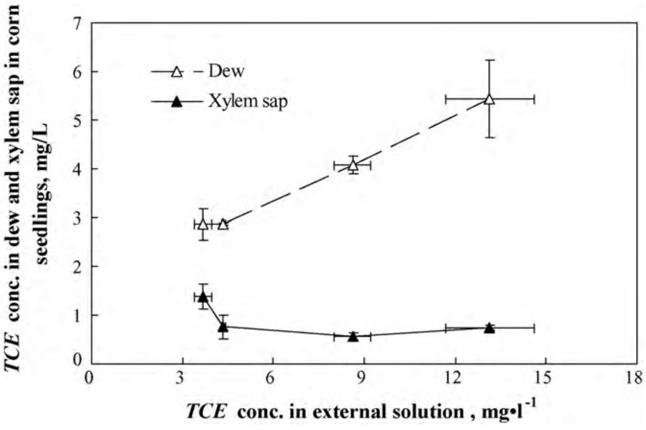

Fig. 3. Change of TCE concentration in dew and in xylem sap in corn seedlings with TCE concentration in external solution. Each point is the mean of three replicates. Error bars represent S.E.

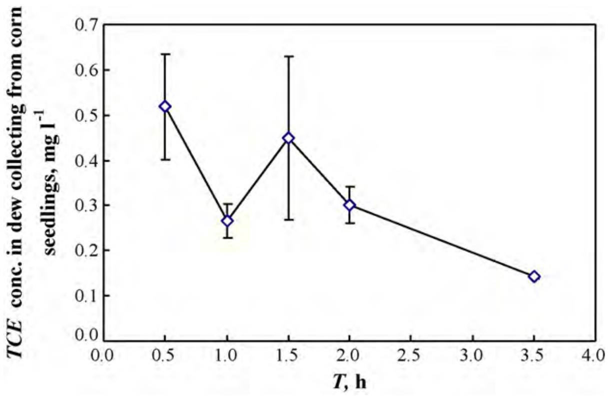

Fig. 4. Change of TCE concentration in control dewdrops collected from corn seedlings with uptake time. Each point is the mean of three replicates. Error bars represent S.E.

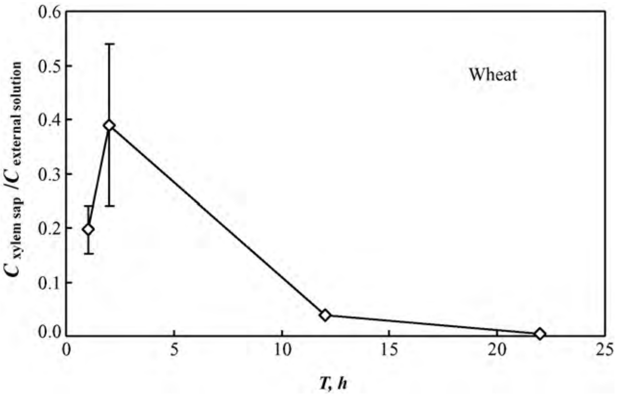

Fig. 5. Change in xylem transport efficiency of TCE in wheat seedlings with uptake time. Each point is the mean of three replicates. Error bars represent S.E.

It is assumed that the equilibrium of a non-polar chemical between barley stem and xylem sap is rapid so that the chemical partition into the stem would be essentially complete after 24 h if the chemical's $\log K_{\text{ow}}$ is less than 3.5 [4]. For passive uptake,

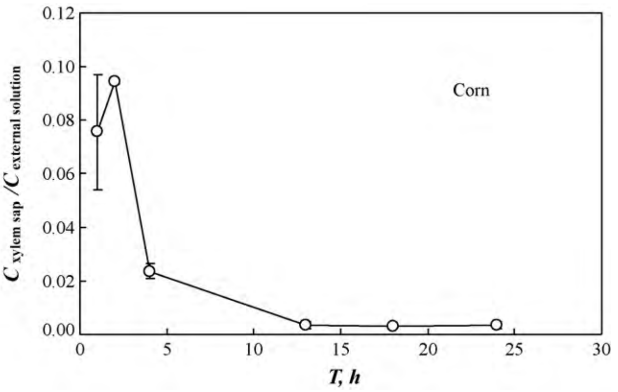

Fig. 6. Change in xylem transport efficiency of TCE in corn seedlings with uptake time. Each point is the mean of three replicates. Error bars represent S.E.

the maximum TSCF value is 1.0. With $\log K_{\mathrm{ow}} = 2.42$ for TCE, the observed TSCFs with both wheat and corn seedlings were far less than 1.0, indicating that the TCE accumulated in plant shoots was far below the equilibrium capacity. A similar effect has been observed in TCE uptake and accumulation by rice seedlings [14].

After TCE entered plant root probably partly via water channels [3], the translocation of TCE in plants could be ascribed to four continuous processes: (1) the partitioning of TCE between plant roots and external water phase; (2) the translocation from roots to shoots via xylem, and from shoots back to roots via phloem if the chemical potential is higher at shoots; (3) the partitioning between xylem sap and organic matter in shoots; (4) the volatilization from shoots to air, and the foliar uptake of vapors by plants if the air phase has a higher chemical potential. Among these processes, the rapid TCE volatilization resulted in a low TCE accumulation in plant shoots [14]. The high downward transport of TCE via phloem increased TCE concentrations in roots and xylem sap, especially at low external TCE solution, since the plants were exposed to the same TCE concentration in the air.

4. Conclusion

TCE could be transported rapidly from plant roots to shoots via xylem. On the other hand, a rapid downward transport via phloem could also occur because of the high exchange efficiency of TCE between plant leaves and air. Due to the complicated TCE upward or downward movement depending on the situation, it is difficult to predict the accumulation of TCE by plants with time using a simple passive process (or partition process) [4,10]. It was observed here that the ratio of TCE concentration in the xylem stream to that in external solution (or the TSCF) [4] decreased rapidly with increasing TCE concentration in external solution or increasing exposure time. The TCE concentration in dewdrops from corn increased sharply with the increasing TCE concentration in external solution in support of the high TCE volatility and the importance of the subsequent foliar uptake by plants. Ratios of the TCE concentration in dewdrops to that in xylem sap with corn leaves ranged from 2 to 8 and were well related to TCE concentrations in external solution. In comparison, the ratios with wheat leaves varied only between 1 and 3, which indicated that TCE exhibited higher volatilization from corn leaves than from wheat leaves. Meanwhile, considering the higher TCE concentrations in both the xylem sap of corn seedlings and final external solution, TCE appeared to exhibit a greater foliar uptake and downward transport via phloem with the corn seedlings than with the wheat seedlings.

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References

[1] H. Li, G.Y. Sheng, W.T. Sheng, O.Y. Xu, Uptake of trifluralin and lindane from water by ryegrass, Chemosphere 48 (2002) 335–341.
[2] E. Wild, J. Dent, G.O. Thomas, K.C. Jones, Visualizing the air-to-leaf transfer and within-leaf movement and distribution of phenanthrene: further studies utilizing two-photon excitation microscopy, Environ. Sci. Technol. 40 (2006) 907–916.
[3] Y.H. Su, Y.G. Zhu, X. Du, Co-uptake of atrazine and mercury by rice seedlings from water, Pesticide Biochem. Physiol. 82 (2005) 226–232.
[4] G.G. Briggs, R.H. Bromilow, A.A. Evans, Relationship between lipophilicity and root uptake and translocation of non-ionised chemicals by barley, Pesticide Sci. 13 (1982) 495–504.
[5] S. Trapp, M. Matthies, Generic one-compartment model for uptake of organic chemicals by foliar vegetation, Environ. Sci. Technol. 29 (1995) 2333–2338.
[6] M. Riederer, Estimating partitioning and transport of organic chemicals in the foliage/atmosphere system: discussion of a fugacity-based model, Environ. Sci. Technol. 24 (1990) 829–837.
[7] S. Paterson, D. Mackay, C. McLarlane, A model of organic chemical uptake by plants from soil and atmosphere, Environ. Sci. Technol. 28 (1994) 2259–2266.
[8] J.G. Burken, J.L. Schnoor, Predictive relationships for uptake of organic contaminants by hybrid poplar trees, Environ. Sci. Technol. 32 (1998) 3379–3385.
[9] P. Weiss, Vegatation/soil distribution of semivolatile organic compounds in relation to their physicochemical properties, Environ. Sci. Technol. 34 (2000) 1707–1714.
[10] C.T. Chiou, G.Y. Sheng, M. Manes, A partition-limited model for the plant uptake of organic contaminants from soil and water, Environ. Sci. Technol. 35 (2001) 1437–1444.
[11] S. Trapp, Plant uptake and transport models for neutral and ionic chemical, Environ. Sci. Pollut. Res. 11 (2004) 33–39.
[12] Y.H. Su, Y.G. Zhu, Transport mechanisms for the uptake of organic compounds by rice (*Oryza sativa*) roots, Environ. Pollut. 148 (2007) 94–100.
[13] X.M. Ma, J.G. Burken, TCE diffusion to the atmosphere in phytoremediation applications, Environ. Sci. Technol. 37 (2003) 2534–2539.
[14] Y.H. Su, Y.C. Liang, Y.G. Zhu, Interactions of mixed organic contaminants in uptake by rice seedlings, Chemosphere 74 (2009) 890–895.