Bioconcentration of atrazine and chlorophenols into roots and shoots of rice seedlings

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Uptakes of o-chlorophenol, 2,4-dichlorophenol, and atrazine at various levels from nutrient solution by roots and shoots of rice seedlings were investigated using a partition-limited model.

Abstract

Accumulation of *o*-chlorophenol (CP), 2,4-dichlorophenol (DCP), and atrazine (ATR), as single and mixed contaminants, from hydroponic solutions into roots and shoots of rice seedlings was studied following 48-h exposure of the plant roots. As single contaminants at low levels, the observed bioconcentration factors (BCFs) of CP and DCP with roots approximated the equilibrium values according to the partition-limited model. The BCF of atrazine with roots was about half the partition limit for unknown reasons. The BCFs of CP and ATR with shoots also approximated the partition limits, while the BCF for more lipophilic DCP with shoots was about half the estimated limit, due to insufficient water transport into plants for DCP. As mixed contaminants at low levels, the BCFs with both roots and shoots were comparable with those for the single contaminants; at high levels, the BCFs generally decreased because of the enhanced mixed-contaminant phytotoxicity, as manifested by the greatly reduced plant transpiration rate.

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1. Introduction

Food crops are susceptible to contamination by various pesticides and organic wastes when exposed to a polluted source, as these chemicals may transport to varying extents into the crops (Lichtenstein, 1960; King et al., 1966; Harris and Sans, 1967; Walker, 1972). The magnitude and efficiency of this transport depend in principle on contaminant level and properties, plant species/composition, exposure time, and other variables.

An understanding of how these parameters affect plant uptake is needed to assess the likely level of crop/plant contamination; this need has promoted a series of investigations on the plant-uptake process in recent time (Briggs et al., 1982, 1983; Topp et al., 1986; Trapp and Matthies, 1995; Trapp et al., 1990; Riederer, 1990; Paterson et al., 1994; Trapp, 1995; Burken and Schnoor, 1997; Weiss, 2000; Chiou et al., 2001; Li et al., 2002; Trapp, 2004; Gao et al., 2005). Analyses of the levels of nonionic contaminants in plants in relation to the external levels in water (or soil water) from extensive sources have revealed that these contaminants enter plants largely via passive (i.e., partition) process (Briggs et al., 1982; Chiou et al., 2001; Trapp, 2004; Gao et al., 2005). In contrast, the plant uptake of electrolytes is mediated by their

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electrical potentials and complex-formation powers (Bromilow and Chamberlain, 1995; Trapp, 2004).

For nonionic organic contaminants with selective plant seedlings, useful empirical equations have been established for estimating the partition uptake by specific plant parts from external water (or other media) under near-equilibrium conditions (Briggs et al., 1982, 1983; Trapp, 1995). For the plant partition uptake in general, where the plants and external water may or may not be close to equilibrium, a quasi-equilibrium partition model may be applied to relate the level in plants (or in a plant part) at a given point of time to the corresponding level in external water (or soil water) (Chiou et al., 2001), namely:

$$C_{pt} = \alpha_{pt} C_w [f_{pw} + f_{pom} K_{pom}] \quad (1)$$

where C_{pt} is the plant-contaminant concentration on the fresh-weight basis and C_w is the concentration in external water (or soil water); f_{pw} and f_{pom} are the respective weight fractions for plant water and plant organic matter; K_{pom} is the contaminant partition coefficient between plant organic matter and plant water; and α_{pt} (≤ 1) is the quasi-equilibrium factor, the ratio of contaminant levels in plant water and external water at a specific point in time. When $\alpha_{pt} = 1$, the contaminant levels in plants and external water are at equilibrium; when $\alpha_{pt} < 1$, the value describes the proximity to the equilibrium state. The C_{pt} -to- C_w ratio, at any point in time or α_{pt} , is called the bioconcentration factor (BCF). When the uptake reaches equilibrium, the BCF is then equal to $[f_{pw} + f_{pom} K_{pom}]$.

With partition-based uptake, the plant-contaminant level is expected to vary with time before it reaches the equilibrium limit, the efficiency toward which is a function of many system parameters, e.g. contaminant partition coefficient, plant/tissue composition, and plant growth transpiration rates. Although the observed contaminant levels in plants/crops from earlier studies (e.g., Briggs et al., 1982; Trapp et al., 1990; Gao et al., 2005) appear to fall largely within the defined partition limits (i.e., $\alpha_{pt} \leq 1$) (Chiou et al., 2001), more extensive experimental tests are necessary for validation and extension of the model. An essential consequence of the partition uptake is the dependence of contaminant levels on specific plant components, due to variations in local compositions and proximities to the external source. Another important consequence is the practical independence of the uptakes by individual contaminants from a multi-component source, provided that the plant growth is not significantly impaired by the contaminants. In current literature, there have been few studies comparing contaminant levels in different plant parts and most published studies have been conducted in single rather than mixed-contaminant systems.

In the present study, the uptakes of atrazine, *o*-chlorophenol, and 2,4-dichlorophenol as single and mixed contaminants by the seedlings of a rice species from nutrient solutions have been determined for model substantiation. The levels for each parent contaminant in plant roots and shoots were quantified separately and analyzed in terms of plant transpiration rates and contaminant partition coefficients with individual cut-dried roots and shoots. This novel approach provides a unique basis for validating the plant-uptake data. Rice plants have been chosen for investigation because they are a major food crop in China that is susceptible to contamination by various pesticides and other chemicals from local pollution sources. Furthermore, there are few published studies on the rice-plant uptake of anthropogenic organic substances in the literature. Whereas atrazine (a widely used herbicide and a weak base) and chlorophenols (common wastewater contaminants and weak acids) represent different chemical types, they also exhibit significantly different partition coefficients to aid in the evaluation of the plant-uptake process.

2. Experimental section

2.1. Preparation of rice seedlings

Seeds of China rice-64 (*Oryza sativa* L.) were disinfected in 30% H_2O_2 (wt:wt) solution for 10 min, followed by thorough washing with de-ionized water. The seeds were germinated in moist perlite. Seven days after germination, the seedlings were transferred to a nutrient solution for continuing growth. Three weeks later, uniform seedlings were selected and transplanted to polyvinylchloride (PVC) pots (7.5 cm diameter and 14 cm high, one plant per pot) for uptake experiments; each pot contained 500 ml nutrient solution with selected contaminants. At this time, the seedling was about 30 cm tall and weighed about 3.5–4.0 g. The composition of the nutrient solution for the experiment was as follows: 5 mM NH_4NO_3 , 12 mM KH_2PO_4 , 2 mM K_2SO_4 , 4 mM $CaCl_2$, 1.5 mM $MgSO_4$, 100 μ M Fe(III)-ethylenediaminetetraacetic acid (EDTA), 10 μ M H_3BO_4 , 1.0 μ M $ZnSO_4$, 1.0 μ M $CuSO_4$, 5.0 μ M $MnSO_4$, 0.5 μ M Na_2MoO_4 , 0.2 μ M $CoSO_4$. The nutrient solution was changed once a week, and its pH value was adjusted to 5.5 using 0.1 M KOH or HCl solution.

2.2. Treatments with contaminants

Compounds used for plant-uptake studies, *o*-chlorophenol (CP), 2,4-dichlorophenol (DCP) were all of analytical grade, and atrazine (ATR), were supplied by Dima Chemical Company in China (purity > 97%), and used as received without further treatment.

Table 1

Organic contaminants used in uptake experiments with rice seedlings: MW = molecular weight; K_{ow} = octanol–water partition coefficient; and pK_a = acid dissociation constant

Contaminant	Abbrev.	MW	$\log K_{ow}^a$	pK_a
<i>o</i> -Chlorophenol	CP	128.5	2.15	8.56
2,4-Dichlorophenol	DCP	163.0	3.30	7.85
Atrazine	ATR	215.7	2.71	1.70 ^b

^a The values for CP and DCP are from Hansch and Leo (1979) and the value for ATR from Trapp et al. (1990).

^b Atrazine is a conjugate acid.

The physicochemical properties of the compounds are listed in Table 1.

In plant-uptake experiments, a series of four-seedlings' sets of comparable sizes were prepared, with their roots being immersed into the same nutrient solutions (ca. 500 mL each). The nutrient solutions containing different added levels of given contaminants were held by a series of identical PVC cylinders. The cylinder was fitted with a PVC septum (7.5 cm in diameter and 0.5 cm in thickness) with a hole drilled at its center (1.5 cm in diameter), through which the plant shoots extended into the outside air space. The section of the shoots passing through the septum hole was wrapped with sponge sheets to minimize the open space. This design prevented the direct water evaporation from the nutrient solution into external air when the seedlings were in place. Hence, the mass of water transpired through plant shoots could be determined accurately by measuring the net weight change of the nutrient solution and plants.

In studies of plant uptakes with single contaminants, the initial contaminant concentrations in nutrient solutions were set at 10, 20, 40, 80 mg L⁻¹ for CP; 10, 20, 40, 80 mg L⁻¹ for DCP; and 2.5, 5.0, 7.5, 10 mg L⁻¹ for ATR. In uptake studies with CP, DCP, and ATR as mixed contaminants, the initial CP/DCP/ATR concentrations (in mg L⁻¹) were set at 10/5/2.5, 20/10/5.0, 40/20/7.5, 80/40/10, and 160/80/12.

2.3. Plant-contaminant equilibration

Preliminary experiments on the uptake of CP, DCP, and ATR from nutrient solution by rice seedlings showed that the solution concentrations of these contaminants approached nearly constant values after 48-h exposure. Thus, the 48-h equilibration was utilized for uptake studies of the three contaminants. The experiments were carried out in a controlled-environment growth chamber that maintained a daily 14-h light period (260–350 $\mu\text{mol m}^{-2} \text{s}^{-1}$) and 25 °C for daytime and 20 °C for nighttime. The relative humidity was set at 70%.

After equilibration, the experimental plants were removed from nutrient solutions, rinsed with distilled water, blotted dry with tissue paper, and sectioned into roots and shoots, the relative weight fractions of fresh

roots and shoots (FW) were determined. The samples were ground with mortar and pestle and subsequently extracted and analyzed for contaminant levels. The detailed analytical procedures are presented later. Control seedlings (grown in solutions without contaminants over the same period) were then removed and sectioned into roots and shoots; the relative weight fractions of fresh roots and shoots (FW) were determined. Half of the sectioned roots and shoots of the control plants were then dried in a chamber (60–70 °C) for 24 h to determine their respective water contents. Over the 48-h study period, the control seedlings showed a weight gain by about 25–30%. The weight gains for experimental plants were generally less (0–20%), depending on the plant-contaminant system and the exposed contaminant level.

2.4. Water transpiration rate

The amounts of water transpired by plants over the 48-h period were determined based on the cumulated weight losses of the plant-solution systems by measuring their weight changes at 1–3 h intervals during 7:00 am and 11:00 pm. After each measurement, the amount of water lost by plant transpiration was replenished with fresh nutrient solution to maintain the total solution volume nearly constant at ca. 500 mL. By this method, the error in amounts of water transpiration was minimized. It also enabled one to quickly detect the change in plant transpiration rate when the plant growth was affected by the contaminant phototoxicity. From the cumulated water-loss weights and the measured fresh plant weights after 48-h exposure, the plant transpiration rates (G) (as g water/g fresh plant weight) were then computed.

2.5. Sorption with cut–dried roots/shoots

The combined cut–dried roots or shoots of control plants were ground into small particle sizes (passing 100 mesh), which were subsequently used to determine the contaminant K_{pom} between plant organic matter and nutrient solution. On the K_{pom} determination, fixed amounts of dried-ground roots or shoots (0.2 g), were added to a series of nutrient solutions (10 mL) containing different initial levels of a given contaminant; the suspensions were equilibrated for 48 h and contaminant concentrations in roots (or shoots) and water after this equilibration period were determined. Average values from duplicate samples were used to construct the sorption isotherms. This equilibration period was found sufficient for establishing contaminant equilibrium between dried-ground roots/shoots and water.

2.6. Analyses of the contaminants

Quantification of CP, DCP, and ATR levels in water from all experiments was achieved by extracting aliquots of respective water samples (0.5 mL) twice with *n*-hexane (3.0 mL), with subsequent combined extracts analyzed for each contaminant by gas chromatography (GC). To determine the levels of these contaminants in fresh roots and shoots, the cut plant samples from each of the four seedlings were weighed, ground, and extracted 4 times with mixed petroleum ether/methylene dichloride (6.5/3.5, v:v; 20 mL), with the combined extracts further cleaned up by passing through a Florisil column (1 cm × 2.5 cm) prior to the GC analyses. The contaminant levels with roots or shoots measured separately with the four plants were then averaged. The quantification and separation of CP, DCP, and ATR as single and mixed contaminants were achieved by an Agilent 6820 gas chromatograph equipped with a ⁶³Ni electron capture detector (ECD) using an HP-5 capillary column (0.32 mm × 30 m × 0.25 μm) and a split injection mode.

A GC oven-temperature program was used to separate the mixed contaminants, which started at 60 °C, increased to 160 °C at a rate of 5 °C min⁻¹, held 1 min, increased to 180 °C at a rate of 2 °C min⁻¹, held 1 min, increased to the final temperature of 210 °C at a rate of 5 °C min⁻¹, and held 10 min. The GC injection-port temperature and the detector temperatures were both set at 250 °C. The average recoveries of CP, DCP, and ATR from plant samples, based on analyses of equilibrated mixtures of contaminants with ground previously-unexposed seedlings, were 96.5 ± 9.3%, 83.9 ± 7.2% and 90.3 ± 6.4% (*n* = 5), respectively. For the water samples, the respective recoveries were 91.4 ± 8.0%, 92.7 ± 5.3% and 100.7 ± 3.1% (*n* = 5). Measured values of plant and water samples were not corrected for the recoveries. In determination of contaminant *K*_{pom} values with dry roots and shoots, the sorbed contaminant masses in roots or shoots were quantified by concentration differences of the contaminants in water before and after 48-h equilibration.

3. Results and discussion

3.1. Dry roots and shoots

The water contents (*f*_{pw}) for roots and shoots of the rice seedlings, calculated from water losses upon drying of the fresh samples, are 0.905 and 0.852, respectively for the roots and shoots. Computed by differences, the respective organic-matter contents (*f*_{pom}) are 0.095 and 0.148 for roots and shoots. The sorption isotherms of CP, DCP, and ATR with dry roots or shoots as sorbents

Fig. 1. Sorption of 2,4-dichlorophenol from nutrient solution to dry roots and shoots of the rice seedlings.

were constructed; the results for DCP as an example are shown in Fig. 1. Based on the *pK_a* values listed in Table 1 and the fixed solution pH (5.5), the measured isotherms are essentially for the unionized contaminant species. The respective *K*_{pom} values derived from the isotherms for the three contaminants with roots and shoots and their standard errors (SE) are summarized in Table 2. The high isotherm linearity with these contaminants is evidence for a partition-equilibrium effect between (dry) roots/shoots and water. The data in Table 2 show that the root organic matter is about 1.8–2.5 times more effective a partition medium for these contaminants than the shoot organic matter. From the measured *f*_{pw}, *f*_{pom}, and *K*_{pom} values, the [*f*_{pw} + *f*_{pom}*K*_{pom}] term in Eq. (1) could then be quantified, as listed in Table 2, for the subsequent analysis of contaminant uptakes by (live) roots and shoots. In Table 2, the *f*_{pom}*K*_{pom}/*f*_{pw} values express the mass distribution ratios of individual contaminants between root/shoot organic matter and plant water in the (live) fresh plants, assuming that a local partition equilibrium prevails (Chiou et al., 2001).

Table 2

Measured partition coefficients (*K*_{pom}) of *o*-chlorophenol, 2,4-dichlorophenol, and atrazine between dry roots/shoots of rice seedlings and water and their respective [*f*_{pw} + *f*_{pom}*K*_{pom}] and *f*_{pom}*K*_{pom}/*f*_{pw} values with fresh roots and shoots

Contaminant	Plant part	<i>K</i> _{pom} (± SE)	[<i>f</i> _{pw} + <i>f</i> _{pom} <i>K</i> _{pom}] ^a	<i>f</i> _{pom} <i>K</i> _{pom} / 2 <i>f</i> _{pw}
<i>o</i> -Chlorophenol	Roots	27.8 (± 2.3)	3.55	2.92
<i>o</i> -Chlorophenol	Shoots	12.1 (± 2.1)	2.64	2.10
2,4-Dichlorophenol	Roots	132 (± 5.5)	13.4	13.8
2,4-Dichlorophenol	Shoots	47.8 (± 3.4)	7.93	8.29
Atrazine	Roots	36.8 (± 2.8)	4.40	3.87
Atrazine	Shoots	20.1 (± 1.7)	3.83	3.49

^a Based on the measured organic-matter contents (*f*_{pom}) of 0.095 and 0.148, respectively, with fresh plant roots and shoots; the respective water contents (*f*_{pw}) with roots and shoots are 0.905 and 0.852.

Thus, on the basis of contaminant partition and local equilibrium, about 70–80% of the CP and ATR levels and 90–99% of the DCP levels in fresh roots/shoots would be associated with the organic matter, with the rest being with plant water.

3.2. Plant uptake: single contaminants

From the measured levels with fresh roots and shoots (C_{pt}) and the associated levels in (nutrient) solution (C_w) for single CP, DCP, and ATR after 48-h exposure, the bioconcentration factors (BCFs), i.e. the C_{pt}/C_w ratios, could be determined. Based on contaminant pK_a values and the presumed physiological $pH < 7$ for rice seedlings, there will be no significant correction of BCFs for molecular dissociation. The quasi-equilibrium factors (α_{pt}) were determined using the measured BCFs and calculated $[f_{pw} + f_{pom}K_{pom}]$ values in Table 2. The results are shown in Table 3. A representative plot of C_{pt} versus C_w for *o*-chlorophenol is depicted in Fig. 2. In these experiments, the plants exhibited only minor growth retardation (relative to controls) during the 48-h period with the applied contaminant levels and there was no obvious sign of phytotoxicity exhibited by each of these contaminants. Over this exposure period, the seedlings gained about 10–20% in weight (relative to ca. 30% for the control). On the other hand, the effects of applied contaminant levels on plant transpiration rates were more distinctive (see Table 4); the transpiration rate decreased by a small extent when exposed to increasing CP level but by a much greater extent when exposed to increasing level of either DCP or ATR.

Consider first the results with plant roots, since the root intake of contaminated water (or soil water) is a common mechanism that leads to the subsequent plant contamination, a subject that has received utmost attention in earlier studies (Briggs et al., 1982; Trapp, 1995, 2004). The observed higher BCF for DCP than for CP and ATR is well consistent with their determined K_{pom} values; the correlation between BCF and K_{pom} for

Fig. 2. Uptake of *o*-chlorophenol alone by rice seedlings from nutrient solution. Each point is the mean of four replicates. Error bars represent SE.

CP and ATR is less obvious because their BCF and K_{pom} values are relatively comparable. The calculated α_{pt} values with roots are reasonably close to 1 for CP and DCP, suggesting that the levels accumulated in roots are near the equilibrium limits; for ATR, with $\alpha_{pt} \approx 0.48$, the level in roots is only about half the equilibrium limit. Considering that ATR and CP have low and comparable K_{pom} values, the cause for the lower root BCF with ATR is not clear. A similar effect has been noted by Briggs et al. (1982) for certain polar (hydrophilic) herbicides (e.g., aldoxycarb) with barley roots, the effect being attributed to the chemical's poor efficiency in passing through plant-lipid membranes. Whether the same occurs for ATR with rice seedlings remains to be examined. Overall, the CP, DCP, and ATR levels with rice roots after 48-h exposure are indicative of near partition equilibrium with external solution, which conforms to the observation for many polar herbicides from nutrient solution into barley roots with 24–48 h exposure (Briggs et al., 1982; Chiou et al., 2001).

The contaminant levels with plant shoots provide a sensitive measure of the contaminant transport into upper plant parts driven by the transpiration stream.

Table 3

BCF (i.e., C_{pt}/C_w) values, levels in hydroponic solutions (C_w), and quasi-equilibrium factors (α_{pt}) of *o*-chlorophenol, 2,4-dichlorophenol, and atrazine as single contaminants with roots and shoots of rice seedlings after 48-h exposure of the plant roots

Contaminant	Plant part	C_w (mg l ⁻¹)	BCF ($\pm$ SE)	α_{pt} ($\pm$ SE) ^a
<i>o</i> -Chlorophenol	Roots	3–40	2.88 ($\pm$ 0.18)	0.81 ($\pm$ 0.05)
<i>o</i> -Chlorophenol	Shoots	3–40	2.74 ($\pm$ 0.22)	1.04 ($\pm$ 0.08)
2,4-Dichlorophenol	Roots	5–18	12.5 ($\pm$ 1.04)	0.93 ($\pm$ 0.08)
2,4-Dichlorophenol	Shoots	5–18	4.27 ($\pm$ 1.14)	0.54 ($\pm$ 0.14)
Atrazine	Roots	1–6	2.11 ($\pm$ 0.17)	0.48 ($\pm$ 0.04)
Atrazine	Shoots	1–6	3.85 ($\pm$ 0.35)	1.00 ($\pm$ 0.09)

^a Calculated with measured BCFs after 48-h exposure together with $f_{pw} = 0.905$ and $f_{pom} = 0.095$ for roots, $f_{pw} = 0.852$ and $f_{pom} = 0.148$ for shoots, and respective contaminant K_{pom} values in Table 1.

Table 4

Relations between transpiration rates (G) of rice seedlings and initial levels of individual contaminants in solutions (C_w^0) to which plant roots were exposed

	<i>o</i> -Chlorophenol		2,4-Dichlorophenol		Atrazine	
	C_w^0	G	C_w^0	G	C_w^0	G
Control plants	0	9.20	0	9.20	0	9.20
Exposed plants	10	8.33	10	6.19	2	6.48
	20	7.28	20	6.62	4	5.83
	40	7.75	40	6.48	6	5.82
	80	7.05	80	4.90	8	4.93

G = mass of water transpired per gram of fresh rice seedlings (g g⁻¹).
 C_w^0 = initial contaminant concentration in solution (mg l⁻¹).

The calculated α_{pt} values with shoots from the observed BCFs, as shown in Table 3, appear to reflect to a good extent the trend for plant passive (partition) uptake. For both CP and ATR, which are more hydrophilic than DCP, the observed α_{pt} values are essentially 1, i.e. the accumulated levels in shoots are close to their equilibrium limits. Over the 48-h exposure with CP and ATR, the observed water transpiration rates ranged from about 5 to 8 times the (fresh) plant weight. These rates exceeded the calculated equilibrium BCFs for CP and ATR, i.e. $F_R[f_{pw} + f_{pom}K_{pom}]_{\text{roots}} + F_S[f_{pw} + f_{pom}K_{pom}]_{\text{shoots}}$, where F_R (0.27) and F_S (0.73) are, respectively, the fresh-weight fractions of roots and shoots. The results with CP and ATR suggest that an efficient systemic water transport (i.e., the upward movement via xylem and downward movement via phloem) occurred within the plant interior that brought the contaminant levels to near-equilibrium limits with the external water. The lower α_{pt} for DCP with shoots (0.54) is expected because DCP has a much higher equilibrium BCF, such that the amount of external water containing DCP transported into the plants (ca. 5–6 g g⁻¹) was insufficient for DCP to satisfy the equilibrium limit with the upper shoots.

3.3. Plant uptake, mixed contaminants

The uptakes by rice seedlings of CP, DCP, and ATR as mixed contaminants from nutrient solution in relation to the exposure levels after 48 h are presented in Table 5. Again, with the measured levels in roots and shoots and the respective levels in solution, the BCFs and α_{pt} values for these contaminants with roots and shoots could be determined. The results are summarized in Table 5. A typical plot of C_{pt} versus C_w for 2,4-dichlorophenol is shown in Fig. 3. The associated plant

Fig. 3. Uptake of 2,4-dichlorophenol as a component in ternary-contaminant mixtures by rice seedlings from nutrient solution. Each point is the mean of four replicates. Error bars represent SE.

transpiration rates for individual mixture systems are given in Table 6.

At low mixed-contaminant levels, the observed BCF or α_{pt} values for CP, DCP, and ATR with plant roots are comparable with the corresponding values for single-contaminant systems. Applicable low C_w ranges are 4–10 mg L⁻¹ for CP, 0.45–1.8 mg L⁻¹ for DCP, and 2–4 mg L⁻¹ for ATR. As noticed, the BCF and α_{pt} values for CP and DCP change remarkably with exposure

Table 5

BCF (i.e., C_{pt}/C_w) values, levels in hydroponic solutions (C_w), and quasi-equilibrium factors (α_{pt}) of *o*-chlorophenol, 2,4-dichlorophenol, and atrazine as ternary mixtures with roots and shoots of rice seedlings after 48-h exposure of the plant roots

Contaminant	Plant part	C_w (mg l ⁻¹)	BCF ($\pm$ SE)	α_{pt} ($\pm$ SE) ^a
<i>o</i> -Chlorophenol	Roots	4–10	2.40 ($\pm$ 0.20)	0.68 ($\pm$ 0.06)
<i>o</i> -Chlorophenol	Shoots	4–10	3.02 ($\pm$ 0.75)	1.14 ($\pm$ 0.28)
<i>o</i> -Chlorophenol	Roots	20–100	0.47 ($\pm$ 0.18)	0.13 ($\pm$ 0.05)
<i>o</i> -Chlorophenol	Shoots	20–100	1.91 ($\pm$ 0.07)	ND ^b
2,4-Dichlorophenol	Roots	0.45–1.8	13.8 ($\pm$ 3.42)	1.03 ($\pm$ 0.26)
2,4-Dichlorophenol	Shoots	0.45–1.8	2.58 ($\pm$ 0.17)	0.33 ($\pm$ 0.02)
2,4-Dichlorophenol	Roots	9–30	2.01 ($\pm$ 0.09)	0.15 ($\pm$ 0.01)
2,4-Dichlorophenol	Shoots	9–30	1.14 ($\pm$ 0.21)	ND
Atrazine	Roots	2–10	1.71 ($\pm$ 0.11)	0.39 ($\pm$ 0.03)
Atrazine	Shoots	2–4	2.92 ($\pm$ 0.52)	0.76 ($\pm$ 0.11)
Atrazine	Shoots	4–10	3.33 ($\pm$ 0.66)	ND ^b

^a Calculated with measured BCFs after 48-h exposure and $f_{pw} = 0.905$ and $f_{pom} = 0.095$ for roots, $f_{pw} = 0.852$ and $f_{pom} = 0.148$ for shoots, and respective contaminant K_{pom} values in Table 1.

^b ND = not determined.

Table 6

Relations between transpiration rates (G) of rice seedlings and initial mixed-contaminant levels in solutions (C_w^0) to which plant roots were exposed

	C_w^0			G
	CP	DCP	ATR	
Control plants	0	0	0	9.2
Exposed plants	10	5	2.5	7.15
	20	10	5.0	5.79
	40	20	7.5	3.07
	80	40	10	3.50
	160	80	12	3.53

G = mass of water transpired per unit fresh weight of the rice seedlings (g g⁻¹).

C_w^0 = initial contaminant concentration in solution (mg l⁻¹).

levels in solution, as discussed later, while the values for ATR are largely independent of the exposure levels ($C_w = 2\text{--}10\text{ mg L}^{-1}$). Over the low mixed CP–DCP–ATR levels, the amount of water transpired decreased somewhat to $6\text{--}7\text{ g g}^{-1}$ (relative to 9.2 g g^{-1} for the control species), and the plant growth was inhibited only slightly by the mixed contaminants relative to that of the control species.

The observed BCF and α_{pt} values of CP, DCP, and ATR with plant shoots are similarly comparable with those of the single-contaminant systems, i.e. DCP exhibits a lower α_{pt} than do CP and ATR due presumably to insufficient water transport to shoots for DCP. Thus, the combined data for the mixture systems at low exposure levels, except the low BCF (or α_{pt}) of ATR with roots, are also reconcilable with the passive-uptake (partition) process, where the plant growth and transpiration are not seriously hampered by the contaminants.

At high mixed-contaminant levels, the systems become more complicated. The BCF and α_{pt} values of CP and DCP with plant roots decrease sharply relative to those at low exposure levels, as shown in Table 5. The observed ranges in C_w are $20\text{--}100\text{ mg L}^{-1}$ for CP and $9\text{--}30\text{ mg L}^{-1}$ for DCP. The marked decreases in BCF and α_{pt} are closely related to the toxicities of the mixed contaminants, as manifested by the nearly total inhibition of plant growth and a large decline in plant transpiration (down to $3.0\text{--}3.5\text{ g g}^{-1}$). Moreover, with high exposure levels, the plant shoots displayed a withering sign during the second day of the exposure, at which time the plant transpiration was nearly shut down ($<1.0\text{ g g}^{-1}$); no withering sign was noticed during the first day. Judging from the magnitudes of the α_{pt} values, the ability of plant xylems to transport water appeared to be seriously impaired during the later stage of the exposure.

With the seedlings exposed to high mixed-contaminant levels, the water contents of the withered shoots fell to $71\text{--}83\%$ (relative to 85% for the control), depending on specific plant species. Since a small decrease in f_{pw} corresponds to a large increase in f_{pom} , the lower f_{pw} with withered plant shoots could significantly increase the $[f_{pw} + f_{pom}K_{pom}]$ term (i.e., the contaminant uptake level) or the related BCF, according to Eq. (1). Thus, apparent large BCFs with withered shoots, despite low BCFs with roots, for CP and ATR at high mixed-contaminant level may be partially an artifact of the moisture loss in plant shoots. In light that the water contents of withered shoots varied to a significant extent between replicate study-plant samples, accurate α_{pt} values for contaminants with shoots at high contamination levels could not be established. As a whole, the measured BCFs at high mixed-contaminant levels are complicated by the high combined phytotoxicity and other unknown effects, making the data evaluation and analysis much more difficult. Nonetheless, the different

BCF data observed with different mixed-contaminant levels are clearly related to the plant's water-transport function, as elucidated by the measured transpiration rates.

4. Conclusions

Most observed BCFs and α_{pt} values for CP, DCP, and ATR at low exposure levels with roots and shoots of the rice seedlings could be well understood in terms of plant passive-uptake (partition) process. The water and organic-matter contents of roots and shoots and the contaminant partition coefficients with the respective (dry) plant fractions enable the contaminant partition limits to be established for assessment of the plant-uptake efficiency. Under conditions where plants maintain relatively healthy growth, the levels of accumulation in both roots and shoots for given contaminants are largely independent of other coexisting contaminants and the observed levels are reconcilable with the measured plant transpiration rates. When the contaminant phytotoxicity severely affects plant growth and transpiration, the plant uptake of contaminants declines. The uptake of more hydrophilic compounds (e.g., CP) tends to more quickly approach the equilibrium limits than less hydrophilic compounds (DCP) over the same exposure period. This is because the attainment of equilibrium for the latter compounds requires more water transport to plants, especially to the upper plant parts, such as shoots. As illustrated, the rate of water transport into plants is a critical factor on the plant uptake of contaminants from a polluted water source.

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