Phytoremediation of Fluorinated Agrochemicals by Duckweed

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Abstract: In natural and engineered systems, aquatic plants actively remediate agricultural wastes and chemicals. Characterization of agrochemical removal by aquatic plants is essential for improved design of phytoremediation systems for polluted surface waters. To measure removal of fluorinated agrochemicals by duckweed, duckweed was exposed to fluorinated phenols in batch reactors. Aqueous fluorinated phenol concentration was regularly sampled and analyzed (HPLC/DAD/MS). After a 50 h exposure, duckweed activity was quantified using an oxygen production assessment to determine whether duckweed was inhibited. Removal of fluorinated phenols by duckweed was rapid, with pseudo-first-order uptake rates of 0.21 to 0.85 L d\(^{-1}\) for fluoro- and trifluoromethylphenols. Uptake rates of fluorinated phenols were compound-specific and appeared to depend on factors affecting rates of enzymatic processing. However, attempts to correlate removal rates with chemical parameters were unsuccessful. The positioning and type of fluoro-substituents on the phenol ring were the most indicative parameters of uptake rates. TFM, a lampricide used in the Great Lakes, was the only fluorinated phenol that was not uptaken by duckweed. Negligible uptake of TFM by duckweed was not attributed to presence of the nitro- or trifluoromethyl- groups, as 2,4,6-trinitrotoluene and 3-trifluoromethylphenol were uptaken. Although uptake rates were not easily predicted by known chemical parameters, uptake rates indicated that duckweed plays an important role in phytoremediation of fluorinated agrochemicals in surface waters.

Keywords. Duckweed, Fluorinated phenols, TFM, Uptake, Water pollution, Wetlands.

Fluorinated organic chemicals, which are commonly used in agriculture, are emerging as a new class of bioaccumulative and persistent pollutants. Use of fluorinated agrochemicals is prevalent and increasing; 28% of halogenated agrochemicals produced since 1940 are fluorinated (Jeschke, 2004). Over 50% of fluorinated agrochemicals are trifluoromethyl-substituted organic chemicals, including the common pesticide trifluralin (Jeschke, 2004; Key et al., 1997). Many fluorinated and trifluoromethyl-substituted agrochemicals are recognized hazards. For example, 3-trifluoromethyl-4-nitrophenol (TFM), a lampricide used in the Great Lakes basin, is an estrogen agonist that possesses an endocrine disruptor effect (EPA, 1999), while 3-aminobenzotrifluoride is a known human toxin. With increasing use of fluorinated organic chemicals as agrochemicals, it is important to investigate the fate of fluorinated organic agrochemicals in both natural and engineered aquatic systems.

In natural and engineered systems, aquatic plants actively remediate agricultural wastes and chemicals. Engineered wetlands and duckweed lagoon systems are commonly used in both rural and urban settings to polish nutrients from agricultural runoff and to treat secondary wastewaters (Cameron et al., 2003; Cheng et al., 2002; Zimmo et al., 2004). As integral components of natural ecosystems, aquatic plants assimilate chemicals that are characteristic of both nonpoint-source and point-source pollutants (Wang et al., 2002; Williams, 2002). Despite the established role of aquatic plants in environmental fate and treatment of pollutants, the interactions between aquatic plants and organic chemicals are not well characterized. Quantitative relationships that describe uptake of emerging organic chemicals by aquatic plants are needed to better understand and design systems to phytoremediate polluted surface waters.

Uptake of organic chemicals by aquatic plants is typically characterized by pseudo-first-order rate coefficients. Studies have indicated that pseudo-first-order uptake rate coefficients are dependent on plant mass and initial chemical concentration (McCutcheon et al., 2003). In contrast, uptake of organic chemicals by terrestrial plants is typically described by an equilibrium concentration factor, such as transpiration stream concentration factors (TSCF) and root concentration factors (RCF). Terrestrial plant concentration factors are measured as the ratio of the concentration of chemical in a specified portion of the plant to the concentration in the external media. Studies have indicated that uptake of organic chemicals by terrestrial plants, as quantified by TSCF and RCF, depend on chemical parameters that describe organic partitioning, such as the octanol-water partitioning coefficient or log K\text{OW} (Briggs et al., 1982; Burken and Schnoor, 1998). However, relationships that have been previously developed for terrestrial plant concentration factors are not necessarily applicable to aquatic plant uptake rate coefficients. For example, uptake of halogenated...
phenols by duckweed was independent of log K_{OW} (Tront et al., 2006), indicating that partitioning of halogenated phenols into duckweed did not control uptake.

Uptake of organic chemicals by plants is typically described as a complex series of processes. Through sorption, diffusion, partitioning, and water translocation, aqueous contaminants accumulate inside plant cells. Continued uptake depends on plant metabolism of these internal organic contaminants, a serial chain of biochemical reactions that includes transformation of parent chemicals, conjugation of metabolites with macromolecules, and incorporation of conjugated products into cell walls and vacuoles (McCutcheon and Schnoor, 2003). The uptake of 2,4-dichlorophenol (2,4-DCP) by aquatic plants, particularly duckweed, has been extensively studied (Day and Saunders, 2004; Pascal-Lorber et al., 2004) and involves many processes typical of uptake of organic chemicals by plants, including abiotic partitioning, conjugation of 2,4-DCP with carbohydrates (i.e., glycosylation), and sequestration into plant tissue (fig. 1). In sum, uptake of organic chemicals by duckweed relies on a complex combination of abiotic and plant-driven processes. Therefore, quantitative relationships that describe uptake of organic chemicals by aquatic plants must consider both abiotic and plant-driven processes.

Improving the design of aquatic plant systems to remediate surface waters requires a better understanding of agrochemical uptake by aquatic plants. The objectives of this study were to evaluate uptake of fluorinated agrochemicals by duckweed and to attempt to develop relationships between uptake rate coefficients and chemical properties. Examination of a subset of fluorinated phenols (i.e., fluorophenols and trifluoromethylphenols) allowed for observations of factors affecting various uptake processes and evaluation of previously determined relationships for uptake. Based on previous studies, it was predicted that enzymatic processing was the rate-limiting step of uptake. Therefore, chemical properties related to enzymatic processing, such as substituent position and type, were more likely to be related to uptake rates than chemical properties related to partitioning, such as log K_{OW} or acid dissociation constants (pK_a).

**MATERIALS AND METHODS**

**COLLECTION AND MAINTENANCE OF DUCKWEED**

Duckweed, identified as *Lemma minor*, was collected from a tertiary wastewater-reclamation wetland located near Atlanta, Georgia, and operated by the Clayton County Water Authority. The wetland is used to polish secondary wastewaters prior to discharge into the raw-water reservoir for the potable-water system of Clayton County, Georgia. Stock duckweed was maintained under simulated natural conditions in laboratory tanks with nutrients supplied from either potting soil or wetland detritus. Duckweed was cultured under an 18 h photoperiod in a growth chamber at 22°C. Prior to experiments, duckweed was thoroughly rinsed with distilled water and weighed, where mass was determined after removal of excess water through a 10 min period of air-drying and blotting with paper towels.

**UPTAKE OF FLUORINATED PHENOLS BY DUCKWEED**

Batch experiments were used to examine effects of chemical structure and related physiochemical properties on uptake rates of fluorinated phenols. Duckweed was exposed to 14 structurally similar fluorophenols and trifluoromethylphenols for 50 h. Three monofluorophenols (FP), three trifluorophenylfluorophenols (TFMeP), four difluorophenols (DFP), three trifluorophenols (TFP), and 3-trifluoromethyl-4-nitrophenol (TFM) were selected as experimental chemicals. For comparison with TFM, uptake of 2,4,6-trinitrotoluene (TNT) was also determined. Experimental chemicals were chosen to permit examination of a suite of similar compounds possessing a range of chemical properties.

Uptake of fluorophenols and trifluoromethylphenols was quantified in batch reactors containing 10 μM fluorophenol or trifluoromethylphenol, 1.0 g duckweed, and 100 mL of Standard Methods media (APHA, 1998). To mimic growth observed in natural and treatment wetlands, a high plant density of approximately 420 g/m² was used. Media pH was buffered to pH 5.0 or 7.0 using 10 mM phosphate buffer. As previous studies have indicated that uptake rates are dependent on the fraction of 2,4-DCP protonated in the external aqueous phase (Tront and Saunders, 2006), media pH was chosen to guarantee that all experimental chemicals were >90% protonated in the media. Aqueous-phase concentrations were sampled over 50 h. Samples were analyzed on a liquid chromatography (LC) system (model 1100, Agilent, Palo Alto, Cal.) equipped with a UV/Vis diode array detector (DAD) and mass spectrometer detector (MSD). Fluorinated phenols were separated from media components using isocratic separation with acetonitrile (40%) and 0.1% acetic acid in water (60%) on a reverse phase SB-C18 analytical column (2.1 × 150 mm, 5 μm, Agilent). Quantification of fluorinated phenols was completed at a wavelength of 210 nm. The absence of aqueous metabolites was monitored using DAD at 210 nm and electrospray ionization (ESI) in negative mode on MSD. Since previous studies have indicated that almost 100% of 2,4,5-trichlorophenol is removed in 50 h (Tront and Saunders, 2006), an exposure period of 50 h was chosen to allow for a short-term determination of uptake. Additionally, plant growth was

![Figure 1. Depiction of uptake of 2,4-dichlorophenol by duckweed. Numbers represent processes associated with uptake: (1) abiotic partitioning; (2) deprotonation internal to the plant cytosol; (3) glycosylation of parent 2,4-DCP with glucose, or glucosylation; (4) glycosylation with apiose; (5) glycosylation with malonate; and (7) sequestration into plant tissue. Figure derived from Day and Saunders (2004) and Tront and Saunders (2006).](image-url)
negligible over 50 h (0.06 ± 0.08 g per 1.0 g duckweed), allowing for elimination of changing plant mass as a variable in uptake.

Oxygen production rates (μmol O₂/h-g duckweed) were quantified at the conclusion of uptake measurements to determine if duckweed was inhibited by fluorinated phenol exposure. The oxygen production rate assessment has been described previously (Reinhold and Saunders, 2006; Tront and Saunders, 2006) and utilized sealed reactors containing 0.5 g duckweed and 60 mL media. After 24 h, the headspace volume was measured with manometers and the partial pressure of oxygen was quantified on a gas chromatograph equipped with a thermal conductivity detector (GC-TCD) and molecular sieve column. Oxygen production rates for exposed and non-exposed duckweed were compared to determine if duckweed was inhibited during uptake measurements.

Microbial and sorption controls were conducted for all experimental fluorinated phenols. To account for microbial degradation and sorption of fluorinated phenols, duckweed was inactivated prior to experimentation through exposure to darkness in sealed reactors for >12 h. After introduction of 10 μM fluorinated phenol, reactors were kept in darkness during the 50 h exposure and measurement period. Since 2-trifluoromethylphenol and 4-trifluoromethylphenol are reported to undergo photolysis (Ellis and Mabury, 2000), reactors containing media and 10 μM trifluoromethylphenol were used to determine if photolytic degradation of trifluoromethylphenols was possible in the experimental reactors. However, it is important to note that the experimental design incorporated full surface coverage of duckweed and coverage of reactor sidewalls, minimizing light inputs into experimental reactors.

Statistical Analyses

Uptake rate coefficients were determined from aqueous concentration data. Aqueous concentrations over time were normalized to initial concentration measurements (i.e., C_t = concentration determined for sample taken at t_1 = 10 min following addition of plants to the media). Sorption studies have indicated that rapid equilibration occurs in the first 10 min of exposure to inactivated duckweed (Tront and Saunders, 2006). Therefore, normalization to C_1 samples accounted for equilibration and for water additions made with addition of plants to reactors. Uptake rate coefficients were established by fitting normalized concentration data with two-parameter, first-order exponential decay relationships with Sigma Plot 2000 (Systat, 2000). If the fit of normalized concentration data did not pass statistical validity criteria (r² > 0.90 and p < 0.01), the uptake rate coefficient was deemed to be zero.

Potential relationships between physiochemical properties of fluorinated phenols and uptake by duckweed were investigated. Experimental values were used when available (Howard and Meylan, 1997). Theoretical KOW values were calculated with the KOWWIN program (EPA, 2002). Acid dissociation constants (pK_a) were determined by SPARC online calculator (Karickhoff et al., 2005) and ACD software (ACD/Lab, 2005). Hammett constants (σ) were determined with established methodology (Hansch and Leo, 1995). Hammett’s constants are used to describe the electron withdrawing or donating nature of substituents and are frequently used to develop relationships between chemicals and enzymes.

Results and Discussion

Uptake of Fluorinated Phenols by Duckweed

Fluorophenols and trifluoromethylphenols were rapidly removed from aqueous media by duckweed. Decreases in aqueous-phase concentrations were attributed to plant-driven uptake, as controls indicated negligible microbial degradation and physiochemical losses in the experimental reactors. No change in concentration was observed in independent control reactors containing trifluoromethylphenols that did not contain duckweed, indicating negligible losses from physiochemical processes, including photolytic degradation and volatilization. Loss of fluorinated phenols in dark reactors with inactivated duckweed was limited to an initial decrease in the first 10 min, which was attributed to sorption. Statistically similar initial decreases were observed in experimental reactors and were accounted for in uptake rate calculations by normalization of concentration to the concentration at 10 min (C_1). Subsequent loss of fluorinated phenols was not observed in the microbial controls, indicating an absence of microbial degradation in experimental reactors. Additionally, oxygen production rates were statistically similar for exposed and non-exposed duckweed, indicating that that initial concentrations (10 μM) did not inhibit duckweed activity.

Aqueous removal typically followed first-order exponential decay relationships, as shown in figure 2. Pseudo-first-order uptake rate coefficients for fluorophenols and trifluoromethylphenols ranged from 0.21 to 0.85 d⁻¹, suggesting rapid aqueous removal of fluorophenols and trifluoromethylphenols by aquatic plants in naturally vegetated and engineered wetland systems.

Effects of Fluorinated Substituents

Further examination of uptake rate coefficients for monofluorophenols and monotrifluoromethylphenols indi—
icated that uptake of trifluoromethylphenols by duckweed was statistically similar to, or greater than, uptake of fluorophenols (fig. 3). Uptake rate coefficients of 2-TFMeP and 2-FP were statistically similar, while uptake rate coefficients for 3-TFMeP and 4-TFMeP were greater than those for 3-FP and 4-FP. It is important to note that no photolytic degradation products were observed in aqueous solution and no loss of 4-TFMeP was observed in experimental reactors systems without duckweed. Consequently, aqueous removal was a plant-driven process and differences in pseudo-first order rate coefficients resulted from unidentified characteristics of the interactions between fluorinated phenols and duckweed.

The observed trend of more rapid uptake of TFMeP than FP was hypothesized to relate to greater electronegativity of the trifluoromethyl substituent and its effects on enzymatic processing of fluorinated phenols by duckweed. Glucosylation, or enzymatic addition of glucose to an organic chemical, is the first enzymatic reaction in the metabolism of 2,4-DCP and other halogenated phenols by duckweed (Day and Saunders, 2004; Ensley et al., 1997; Pascal-Lorber et al., 2004). It was assumed that similar metabolic pathways exist for the fluorinated phenols studied herein. After abiotic partitioning of halogenated phenols in plant cells, halogenated phenols must deprotonate before glucosylation can occur. Deprotonation may occur either from acid-base equilibrium within the plant cytosol or through action of glucosyltransferases prior to transfer of glucose to the halogenated phenol. In either case, availability of an easily deprotonated hydroxyl group could affect rates of enzymatic processing.

In the meta and para positions, the trifluoromethyl group (TFMe) would more greatly affect stability of the hydroxyl group, as evidenced by lower acid-base dissociation constants (i.e., pK_a,2-TFMe = 8.8 vs. pK_a,2-F = 9.3, pK_a,4-TFMe = 8.1 vs. pK_a,4-F = 9.6). In the ortho position, the effect of trifluoromethyl group on the hydroxyl group is subtler, and the difference between pK_a of 2-TFMeP and 2-FP is lower (i.e., pK_a,2-TF = 8.1 vs. pK_a,2-F = 8.5). Additionally, the trifluoromethyl group in the ortho position may negatively affect enzymatic glucosylation through negative proximity effects, including hydrogen bonding between the trifluoromethyl group and the hydroxyl group (Kovács et al., 1996) or steric hindrance of glucosyltransferases responsible for conjugating halogenated phenols. In other words, the trifluoromethyl group in the ortho position may interfere with the ability of glucosyltransferase to interact with 2-TFMeP. Consequently, variations in uptake rate coefficients for trifluoromethylphenols and fluorophenols were attributed to availability and accessibility of the ionized hydroxyl group to the glucosyltransferase enzyme.

A positive, linear correlation was observed between uptake rate coefficients (k) and Hammett’s constant (σ) for monofluorophenols, where k (d⁻¹) = 0.19 + 0.41σ (r² = 0.997, p = 0.05). These results indicated that differences in uptake rate coefficients might be attributed to differences in enzymatic rates, as similar relationships have been observed for mono-substituted phenols’ interactions with enzymes. For example, activity of tyrosinase toward monofluorophenols was dependent on σ (Battaini et al., 2002). Additionally, activity of a glucosyltransferase isolated from pig liver towards para-substituted phenols increased linearly with increasing σ (Magdalou et al., 1982). However, both these relationships, and the one found in this study, were confined to rigidly defined classes of chemicals with few compounds (e.g., three monofluorophenols, ten para-substituted phenols). Furthermore, a similar relationship was not observed for trifluoromethylphenols, difluorophenols, or trifluorophenols. Consequently, while both uptake rates and enzymatic transformation rates of monofluorophenols were correlated with σ, these results solely indicate the importance of considering enzymatic conjugation rates in the uptake of organic chemicals by duckweed. Hammett’s constant (σ) was not indicative of patterns of uptake rates.

The effect of substituent positioning on uptake rate coefficients was examined with eight ortho-substituted fluorophenols. Uptake rate coefficients ranged from 0.26 to 0.84 d⁻¹ (fig. 4). Uptake rate coefficients of difluorophenols (0.27 ± 0.04 to 0.67 ± 0.03 d⁻¹) and trifluorophenols (0.30 ± 0.04 to 0.84 ± 0.07 d⁻¹) bracketed the uptake rate coefficient of 2-FP (0.44 ± 0.03 d⁻¹), indicating independence of uptake rate coefficients on number of fluorine substituents. Results supported the hypothesis that substituent position affects uptake rate coefficients. Fluorine substitution in both ortho-positions (i.e., 2,6-DFP, 2,3,6-TFP, and 2,4,6-TFP) hindered uptake, as evidenced by uptake rate coefficients of 0.27 ± 0.04 d⁻¹, 0.37 ± 0.05 d⁻¹, and 0.30 ± 0.04 d⁻¹, respectively. However, this explanation is not adequate for hindered uptake of 2,5-DFP (0.34 ± 0.04 d⁻¹), illustrating the complex nature of uptake of fluorinated phenols by duckweed.

Hindered uptake of ortho-, ortho-substituted fluorophenols was attributed to inhibition of the glucosyltransferase enzyme. As glucosylation of fluorophenols requires approach of the fluorophenol to within bonding distance of activated glucose and the enzyme, a negative proximity effect was considered a probable explanation for decreased uptake rates of ortho-, ortho-substituted fluorophenols. Two potential proximity effects were considered: steric hindrance, and repulsion between the ortho-fluorine and the enzymatic reaction site. Studies utilizing a glucosyltransferase from Sorghum bicolor (UGT85B1) have indicated that UGT85B1 activity required availability of sterically unin-

Figure 3. Uptake rate coefficients for fluorinated phenols based on position of fluoro (F) and trifluoromethyl (TFMe) substituents determined through two experiments (Trial 1 and Trial 2). Numbers in parentheses are estimated pK_a values. Error bars represent standard error of determination for composite data from triplicate reactors.
Figure 4. Uptake rate coefficients for fluorinated phenols based on substituent position. Error bars represent standard errors of determination for composite analysis of triplicate reactors.

Figure 5. Uptake rate coefficients versus fraction of halogenated phenol protonated at cytosolic pH. Error bars represent standard error based on triplicate reactors.

Effects of Partitioning-Related Properties

Previous experiments had indicated a tentative, positive correlation between pseudo-first-order uptake rate coefficients and the fraction of halogenated phenol protonated internal to the plant cell ($r^2 = 0.66$) (Tront et al., 2006). It was then hypothesized that halogenated phenols, once internal to the plant cell, had to partition through membranes to reach glucosyltransferase enzymes. If this hypothesis was true, then the ionized state of the halogenated phenol at intercellular or specifically cytosolic, pH would play an important role in uptake and conjugation of organic chemicals. However, the previous hypothesis did not explain trends observed for fluorinated phenols, and uptake rate coefficients did not depend on the fraction of fluorinated phenol protonated at cytosolic pH (fig. 5). Uptake rate coefficients were independent of the fraction protonated at cytosolic pH, whether the fraction protonated was calculated from experimental or estimated (i.e., SPARC and ACD) $pK_a$ values. It is important to consider uncertainties inherent to relationships that rely on the fraction of halogenated phenol protonated in the plant cytosol. Of 13 fluorinated phenols studied herein, experimental $pK_a$ values were only published for five (Mackay et al., 1997). SPARC and ACD estimations of $pK_a$ varied by as much as 0.90 pH units, and errors associated with ACD estimations were as large as 0.23 pH units. In respect to the fraction protonated at pH 7, these errors were substantial enough to hinder analysis; for example, the ACD-estimated $pK_a$ of 2,4,6-TFP is 7.47 ± 0.23, which yields a fraction protonated at pH 7.0 of 0.72 ± 0.09. Consequently, the relationship between uptake rate coefficients and the fraction of fluorinated phenol protonated at pH 7.0 could be hidden by uncertainties and error associated with estimated and experimental $pK_a$ values. Nonetheless, fluorinated phenol results were inconsistent with the previous hypothesis that the fraction of organic chemical protonated at cytosolic pH is correlated with uptake rate coefficients. Consequently, while the electronegativity of the substituents may play a role in destabilizing the ring to allow faster glucosylation (as observed for monotrifluoromethylphenols vs. monofluorophenols), $pK_a$ could not be used to predict uptake rates when external partitioning was not a factor. It is important to note that $pK_a$ was an important parameter affecting partitioning of organic chemicals into plant cells when the external medium pH was near or less than the $pK_a$ (Tront and Saunders, 2006).

Relationships between physiochemical properties related to partitioning, such as hydrophobicity ($K_{OW}$), and uptake rate coefficients were also investigated. Partitioning param-
HINDERED UPTAKE OF TFM: COMPARISON WITH TNT

Uptake of TFM, a lampricide used in the Great Lakes, was studied to investigate the impact of duckweed on aqueous depletion of aquatic pesticides. Aqueous removal of approximately 14 μM TFM in 50 h was not statistically significant (fig. 6), even though oxygen production rates indicated that duckweed was not inhibited by TFM. As 3-TFMeP was rapidly removed (fig. 6), it was initially hypothesized that introduction of a charged nitro- group to the phenolic ring prevented partitioning of TFM into plant tissue. However, uptake of 2,4,6-trinitrotoluene (TNT) by duckweed was inconsistent with this hypothesis. It is important to note that phytotransformation of TNT follows a different pathway than halogenated phenols (Bhadra et al., 1999; Hughes et al., 1997); consequently, experiments with TNT only addressed the hypothesis that charged nitro- groups prevented abiotic partitioning into duckweed and did not address potential differences in metabolic processing rates of TNT, TFM, and 3-TFMeP. Therefore, the inability of duckweed to uptake TFM was attributed to an absence of intrinsic metabolic pathways capable of transforming or conjugating TFM and was not associated with partitioning processes. The high electronegativity of combined nitro- and trifluoromethyl-groups on TFM could account for hindered enzymatic processing of this agrochemical.

CONCLUSIONS

Understanding the environmental fate of organic chemicals is essential to protecting human health, endangered species, and future food and water resources. Additionally, characterization of chemical uptake rates in duckweed systems is essential for the future design of phytotechnologies intended for removal of agrochemicals from water resources. This study advanced understanding of the attenuation of fluorinated agrochemicals by duckweed and examined the uptake processes that occur in both natural ecosystems and engineered wetlands designed for nutrient removal. Uptake of fluoroanilines and trifluoromethylphenols by duckweed was a rapid process, indicating great potential for aquatic plants to remediate fluorinated agrochemicals in both engineered and natural systems. Uptake was dependent on fluorinated substituent type and position, but was independent of partitioning-related properties, such as KOW and pKa. Results indicated that enzymatic processing of fluorinated phenols by plants is an important mechanism of uptake, and the presence of multiple isoenzymes capable of conjugating structurally similar organic chemicals was suggested. Additionally, uptake of TNT by duckweed indicated that the nitro-substituent of TFM did not prevent uptake, emphasizing again the importance of enzymatic processing in uptake of organic chemicals by aquatic plants.

To investigate more fully the role of enzymatic processing in uptake of fluorinated agrochemicals by duckweed, future research includes development of duckweed callus and cell-suspension cultures. By increasing surface area and minimizing partitioning limitations, duckweed cell-suspension cultures should allow quantification of metabolic processing rates. Additional investigations into the effects of different design parameters, such as temperature, concentration, and plant density, are ongoing.

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