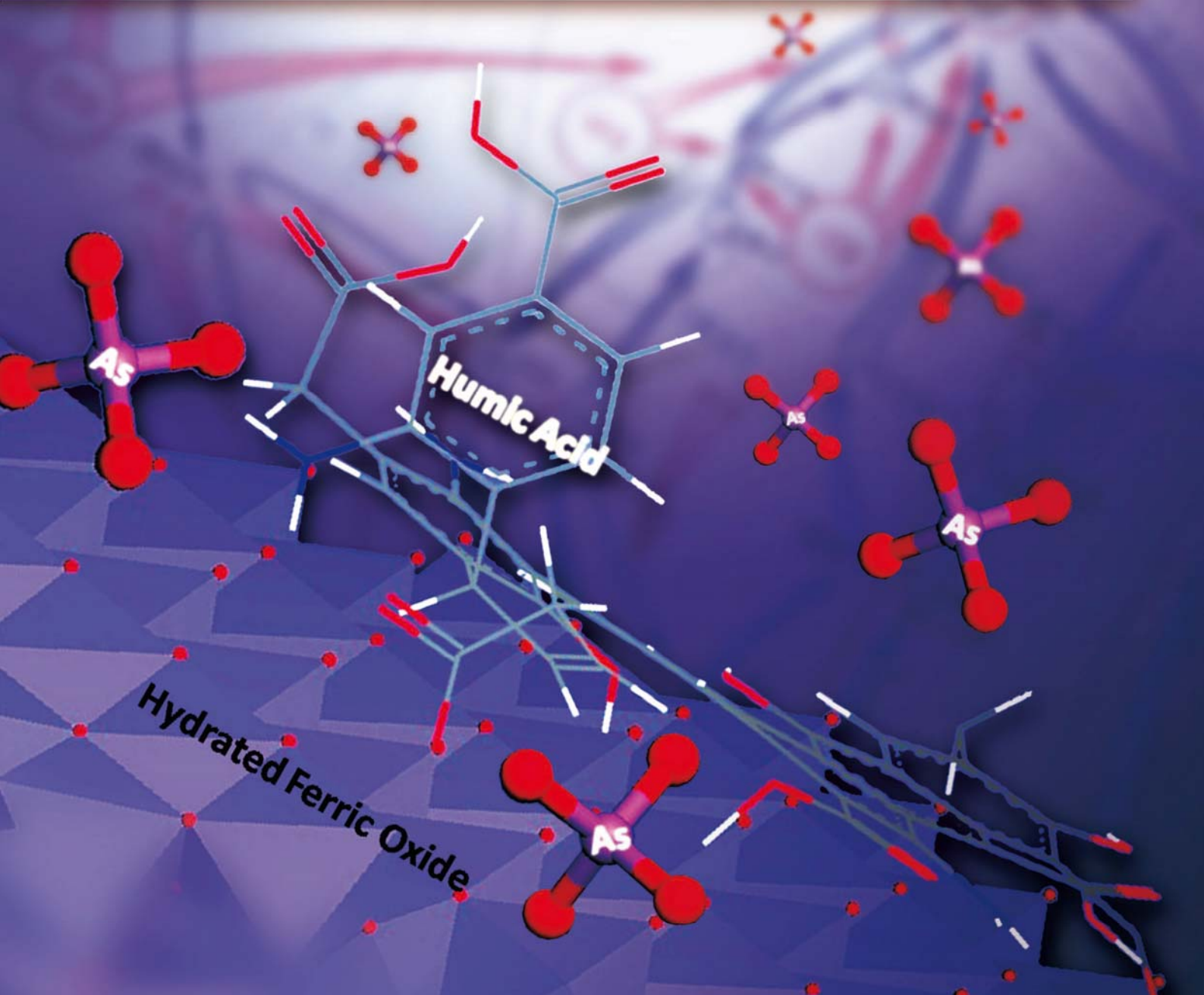
JES
JOURNAL OF ENVIRONMENTAL SCIENCES
ISSN 1001-0742
CN 11-2629/X
February 1, 2014 Volume 26 Number 2
www.jesc.ac.cn



ELSEVIER
Science Press
Sponsored by
Research Center for Eco-Environmental Sciences
Chinese Academy of Sciences

ISSN 1001–0742 **Journal of Environmental Sciences** Vol. 26 No. 2 2014

CONTENTS

Aquatic environment

Atmospheric environment

Environmental health and toxicology

Environmental catalysis and materials

Serial parameter: CN 11-2629/X*1989*m*261*en*P*30*2014-2

Journal of Environmental Sciences 26 (2014) 315–322

Available online at www.sciencedirect.com

Journal of Environmental Sciences

www.jesc.ac.cn

A comparison on the phytoremediation ability of triazophos by different macrophytes

Zhu Li[1,4], Huiping Xiao[3], Shuiping Cheng[2,*], Liping Zhang[1], Xiaolong Xie[1,*], Zhenbin Wu[1]

1. State Key Laboratory of Freshwater Ecology and Biotechnology, Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, China. E-mail: lizhu1985@foxmail.com

2. Key Laboratory of Yangtze River Water Environment, Ministry of Education, Tongji University, Shanghai 200092, China

3. Wuhan Yangtze Business University, Wuhan 430072, China

4. University of the Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 12 March 2013
revised 08 May 2013
accepted 21 May 2013

Keywords:
pesticide
removal capacity
relative growth rate
bio-concentration factor
transfer factor
root/shoot ratio
factor analysis

DOI: 10.1016/S1001-0742(13)60417-9

ABSTRACT

The strategy of choosing suitable plants should receive great performance in phytoremediation of surface water polluted by triazophos (O,O-diethyl-O-(1-phenyl-1,2,4-triazol-3-base) sulfur phosphate, TAP), which is an organophosphorus pesticide widespread applied for agriculture in China and moderately toxic to higher animal and fish. The tolerance, uptake, transformation and removal of TAP by twelve species of macrophytes were examined in a hydroponic system and a comprehensive score (CS) of five parameters (relative growth rate (RGR), biomass, root/shoot ratio, removal capacity (RC), and bio-concentration factor (BCF)) by factor analysis was employed to screen the potential macrophyte species for TAP phytoremediation. The results showed that *Thalia dealbata*, *Cyperus alternifolius*, *Canna indica* and *Acorus calamus* had higher RGR values, indicating these four species having stronger growth capacity under TAP stress. The higher RC loading in *Iris pseudacorus* and *Cyperus rotundus* were 42.11 and 24.63 μg/(g fw·day), respectively. The highest values of BCF occurred in *A. calamus* (1.17), and TF occurred in *Eichhornia crassipes* (2.14). Biomass and root/shoot ratio of plant showed significant positive correlation with first-order kinetic constant of TAP removal in the hydroponic system, indicating that plant biomass and root system play important roles in remediation of TAP. Five plant species including *C. alternifolius*, *A. calamus*, *T. dealbata*, *C. indica* and *Typha orientalis*, which owned higher CS, would be potential species for TAP phytoremediation of contaminated water bodies.

Introduction

Triazophos (O,O-diethyl-O-(1-phenyl-1,2,4-triazol-3-base) sulfur phosphate, TAP) is an efficient and broad-spectrum organophosphorus pesticide used as insecticide, nematicide and acaricide, which is widely used in Chinese agricultural industry to protect various crops like cotton, rice, fruits, oil seeds and vegetables (Qu et al., 2003; Gui et al., 2006; Li et al., 2008). The toxicity of TAP attracted considerable public attention over the last decades. It was reported that TAP has fairly high toxicity to aquatic creatures and shows threat to the water ecosystem health (Zhong et al., 2009; Naveed et al., 2010; Jain et al., 2011). Zhang et al. (2011) showed that TAP chronic dietary intake risk for aged persons and that an acute nutritional intake risk of TAP residues in apple, cabbage, rice and wheat meal reaches an unacceptable range in China.

In the past few years, phytoremediation is of great concern as a cost-efficient and eco-friendly technology

*Corresponding author. E-mail: shpcheng@tongji.edu.cn (Shuiping Cheng); xxl594518@163.com (Xiaolong Xie)

that uses plants and their associated rhizosphere microbes to remove, transform, or contain contaminants located in soils, sediments, surface water, and ground water (Alkorta and Garbisu, 2001; Susarla et al., 2002; Gerhardt et al., 2009). Many authors have reported the role of plants in remediating soils and water contaminated with organic pollutants. Burken and Schnoor (1997) found that hybrid poplar trees could uptake, hydrolyze and dealkylate atrazine to less toxic metabolites. The study by Gao et al. (2000a) showed that selected aquatic plants have the potential to accumulate and metabolize organophosphorus compounds. The feasibility study of phytoremediation to TAP has also been proved. In our previous studies, plants play a leading role in removal of TAP in hydroponic systems and *Canna indica* shows the potential of phytoremediation of TAP from contaminated water (Cheng et al., 2007; Xiao et al., 2010a, 2010b). Consequently, phytoremediation is a sound approach to remediate TAP pollution from the ecosystem.

In recent years, differences in ability of phytoremediation among plant species were well recognized (Gao et al., 2000b; Hutchinson et al., 2001; White et al., 2005), therefore selecting suitable plants should receive great attention as an effective phytoremediation approach. Although there has been a growing interest in the purification efficiency of plants relative to remediate organophosphorus pesticides, little information is available regarding the plant species involving the phytoremediation of TAP and the effectiveness of these plants to remediate TAP from contaminated water. In this research, several macrophytes, which are available in China and commonly used in constructed wetlands, were chosen for experiment in a hydroponic system to study the ability of different plant species to remediate TAP. A comprehensive score (CS) was employed by factor analysis to compare the potential plant species for TAP phytoremediation.

1 Materials and methods

1.1 Materials and treatment

Twelve common macrophytes were collected from the East Lake of Wuhan (Hubei Province, China). These plants were *Acorus calamus* Linn., *Canna indica* Linn., *Cyperus alternifolius* Linn. subsp. *flabelliformis* (Rottb.) Kukenth., *Cyperus rotundus* Linn., *Eichhornia crassipes* (Mart.) solms, *Iris pseudacorus* Linn., *Phragmites australis* (Cav.) Trin. ex Steud., *Pontederia cordata* Linn., *Scirpus triangulates* Roxb., *Thalia dealbata* Fraser ex Roscoe, *Typha orientalis* Presl and *Vetiveria zizanioides* (Linn.) Vach. All plants were washed by deionized water and pre-cultivated in nutrient medium for 7–10 days before experiment. The nutrient medium consisted of (mg/L) KNO_3 (50.5), $Ca(NO_3)_2$ (118), $MgSO_4$ (24), KH_2PO_4 (13.6), HBO_3 (286), $MnCl_2{\cdot}4H_2O$ (181), $ZnSO_4{\cdot}7H_2O$ (22), $CuSO_4{\cdot}5H_2O$ (8), $H_2MoO_4{\cdot}H_2O$ (2), $FeSO_4{\cdot}7H_2O$ (28) and EDTA-Na_2 (37). TAP (emulsifying concentrate 80%) was purchased from Deshijia Chemical Pesticide Consultation Center (Shandong Province, China).

Plants with similar biomass were selected from each species and transplanted to conical flask containing 2 L nutrient medium, and twelve groups were set up with different plant species. Taking into account that the usual TAP residual concentration of soil leachate was lower than 1 mg/L (Bosch et al., 2005), control and three treatments with three replicates were set up, including 0, 1, 3, 5 mg/L of TAP, respectively. In addition, a non-plant group consisting of nutrient medium with 1, 3, 5 mg/L of TAP was set to calculate the TAP removal by photolysis, hydrolysis and microbial degradation in non-plant hydroponic system. All plants were cultivated under similar conditions with room temperature (25 ± 5°C) and natural illumination (light intensity 34.5 ± 7.1 μmol/(sec·m^2), 14 hr:10 hr of day/night). Water loss from evaporation and transpiration by plants was compensated by adding deionized water every five day.

1.2 Chemical analysis

Water samples for TAP analysis were sampled every 5 days and then pretreated according to the methods of Zhang et al. (2005). The samples were centrifuged at 15,000 r/min at 25°C for 10 min and a volume of 1.5 mL of the supernatants was prepared for the analysis of TAP concentration. TAP concentration was measured by high performance liquid chromatography (HPLC) (1100 serial, Agilent, USA), which was furnished with a DAD detector. Water RP-C18 column (5 μm, 3.9 mm × 150 mm inner diameter, Waters, USA) was used for separation. Analytes were eluted with water-methanol (3:7, *V/V*) mixture at a flow rate of 1.00 mL/min. UV detection was made at 246 nm for TAP and retention time was 6.79 min with the column temperature of 25°C.

The treatment lasted 20 days. The plants were harvested and were separated into three sections (roots, stems and leaves) for recording fresh weight, and then replicates of each section of each group in the same treatment were composited respectively for TAP determination in the end of experiment. TAP in plant samples was analyzed using the method of Xiao et al. (2010a). Plant samples were extracted with 0.01 mol/L $CaCl_2$ and methanol, and then freeze-dried, homogenized and extracted with acetone. The supernatant condensed and eluted through a chromatographic column. The eluent condensed and readied to post-HPLC detection. The method of TAP detection for plant organs was similar to the HPLC method described above, with several conditions adjusted as follows: the water-methanol ratio of mobile phase was changed into same size ratio (*V/V*) and the retention time for TAP was transformed into 17.57 min.

1.3 Data analysis

The relative growth rate (RGR, mg/(g fresh weight (fw)·day) was calculated for total biomass by Eq. (1) (Blackman 1919):

$$\mathrm{RGR} = \frac{\ln W_2 - \ln W_1}{t_2 - t_1} \times 1000 \quad (1)$$

where, W_1 (g) and W_2 (g) indicated the initial and final plant fresh weights, respectively. And (t_2-t_1) (day) indicated the experimental time.

The TAP removal in the hydroponic system adapts to the kinetics of a first-order decay model (Gao et al., 2000a) , which could be described by Eq. (2):

$$C_t = C_0 \times \mathrm{e}^{-k \times t} \quad (2)$$

where, k (day^{-1}) indicated the first-order kinetic constant. C_0 (mg/L) and C_t (mg/L) indicated the TAP concentration at the beginning and time t (day) in the hydroponic solution, respectively.

According to Eq. (2), the TAP removal (R_t) by plant and microbial degradation promoting by plant at time t (day) was derived by Eq. (3):

$$\begin{aligned} R_t &= R_{\mathrm{G},t} - R_{\mathrm{N},t} \\ &= (C_{t-1} - C_{t-1} \times \mathrm{e}^{-g}) \times V - (C_{t-1} - C_{t-1} \times \mathrm{e}^{-n}) \times V \\ &= C_{t-1}(\mathrm{e}^{-n} - \mathrm{e}^{-g}) \times V \\ &= C_0 \times \mathrm{e}^{-g(t-1)}(\mathrm{e}^{-n} - \mathrm{e}^{-g}) \times V \end{aligned} \quad (3)$$

where, $R_{\mathrm{G},t}$ (mg) indicated the gross TAP removal at time t (day) by combined action of plant, microbe, photolysis and hydrolysis in hydroponic system, and $R_{\mathrm{N},t}$ (mg) indicated the TAP removal at time t (day) by photolysis, hydrolysis and microbial degradation in non-plant hydroponic system. C_{t-1} (mg/L) indicated the TAP concentration at time (t-1) (day). V (L) indicated the volume of nutrient medium. g (day^{-1}) and n (day^{-1}) indicated the first-order kinetic constant in plant hydroponic system and non-plant hydroponic system, respectively.

The fw of plant was given by Eq. (4):

$$M_t = M_0 + m \times t \quad (4)$$

M_0 and M_t meant the initial fw (g) and the fw at time t (days). m (g) indicated the increase of fresh weight per day.

The TAP removal capacity (RC) of plant was expressed as μg per gram of fw by day (Olette et al., 2008). Combined with Eqs. (2), (3) and (4), RC (μg/(g fw·day)) of plant was calculated by Eq. (5):

$$\mathrm{RC} = \frac{\sum_{t=1}^{20} \frac{C_0 \times \mathrm{e}^{-g(t-1)}(\mathrm{e}^{-n} - \mathrm{e}^{-g}) \times V}{(M_0 + m \times t)}}{20} \quad (5)$$

Biomass was the average of initial and final fresh weight of plant. Root/shoot ratio was calculated by the ratio of plant root biomass to shoot biomass. Bio-concentration factor (BCF) was defined as the ratio of TAP concentration in the plant tissue and that in the culture solution at harvest (Kelsey and White 2005). Translocation factor (TF) was estimated by the ratio of TAP concentration in plant shoot and that in root at harvest (White et al., 2005). The average values of BCF and TF of each species were the average of three treatments. All reported TAP concentrations in plant were on a dry weight basis.

All the statistical analyses were performed by SPSS Statistics19 (SPSS Inc., Chicago, IL, USA). P values of less than 0.05 were considered to be statistically significant. Differences in RGR of each species among four TAP concentrations and differences in average RGRs of four TAP concentrations among twelve plant species were separately analyzed by One-Way ANOVA followed by a Student-Newman-Keuls multiple comparison test. Because of the large scattering of data and failing ANOVA, differences in RGR of each species in control, differences in average values in RC, BCF and TF between each other species were separately assessed by nonparametric tests for several independent samples followed by a Kruskal-Wallis test. Bivariate correlation analysis was calculated to study the dependence relations between parameters. Factor analysis was used in comprehensive comparison on five parameters (biomass, RGR, RC, BCF and root/shoot ratio) of twelve species of macrophytes, and two components were extracted. CS of those plants was calculated by Eq. (6):

$$\mathrm{CS} = C_1 \times R_1 + C_2 \times R_2 \quad (6)$$

where, C_1 and C_2 indicated the score of component 1 and component 2, respectively. R_1 and R_2 indicated the contribution rate of component 1 and component 2, respectively.

2 Results and discussion

2.1 Effect of TAP on the growth of different macrophytes

To be suitable for phytoremediation, a plant should grow healthy when exposed to contaminated water. RGR can reflect the plant capacity for survival and growth under TAP stress. The RGRs of twelve macrophytes with four TAP concentration levels are depicted in **Fig. 1**. Results

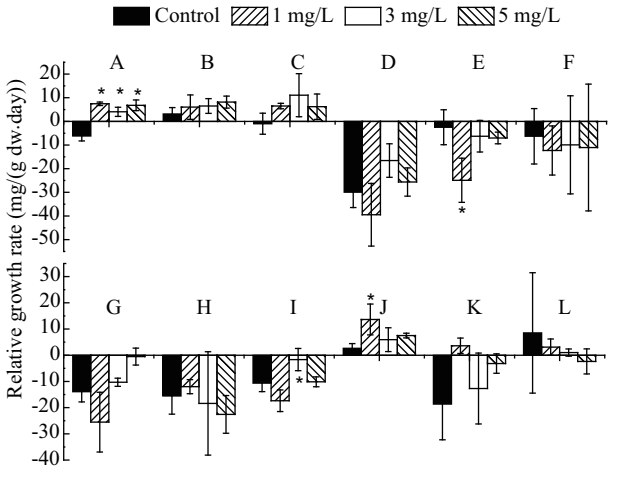


Fig. 1 Relative growth rates (RGR) of twelve macrophytes exposed to TAP at 0, 1, 3 and 5 mg/L during 20 days. Error bars represent standard error of three replicates. * Significantly different from control ($P < 0.05$). A: *Acorus calamus*; B: *Canna indica*; C: *Cyperus alternifolius*; D: *Cyperus rotundus*; E: *Eichhornia crassipes*; F: *Iris pseudacorus*; G: *Phragmites australis*; H: *Pontederia cordata*; I: *Scirpus triangulates*; J: *Thalia dealbata*; K: *Typha orientalis*; L: *Vetiveria zizanioides*.

showed that there were significant differences of RGRs among the twelve plants in control. The RGRs of *C. indica*, *T. dealbata* and *C. alternifolius* were significantly greater than that of *C. rotundus* ($P < 0.05$), indicating that the former three plants are suitable for the culture in this hydroponic system, but the last plant is not. This phenomenon might be due to the fact that different plant species request different nutrients, light and/or temperatures. The maximum and minimum value of average RGRs in fw all these treatments was 7.43 mg/(g·day) for fw *T. dealbata* and –27.91 mg/(g·day) for *C. rotundus*, respectively. In comparision, the RGRs of *T. dealbata*, *C. alternifolius*, *C. indica* and *A. calamus* were significant greater than those of *T. orientalis*, *I. pseudacorus*, *E. crassipes, S. triangulates*, *P. australis*, *P. cordata* and *C. rotundus* ($P < 0.05$), indicating the former four plants have stronger growth capacity under TAP stress.

Results also showed that the RGRs of *A. calamus* in all treatments, *S. triangulates* in 3 mg/L TAP were significantly larger than those in control, that of *E. crassipes* and *T. dealbata* in 1 mg/L TAP was significantly smaller than its control, and that the other plant species showed no significant difference between their control and treatments. The different response in growth of these twelve species may be caused by the reasons on: (1) plant species differ in their phosphorus requirement (Föhse et al., 1988). TAP can be hydrolyzed into inorganic phosphorus, which can be utilized by plants and promotes their growth (Rani et al., 2001; Cheng et al., 2007); (2) plant species have different tolerance to pesticides (Olette et al., 2008). TAP can affect physic-biochemical characteristics of a plant and inhibit its growth (Xiao et al., 2008).

2.2 Removal of TAP by different macrophytes

The removal kinetics constant (k) can reflect the total removal rate of TAP by combined action of plant, microbe, photolysis and hydrolysis in hydroponic system. The k value of non-plant group (**Table 1**) was 0.006, which was far lower than that of plant groups, indicating that plant a play key role in TAP removal of plant hydroponic system. A significant positive correlation existed between k and root/shoot ratio ($R^2 = 0.603$, $P < 0.01$), which was used to calculate the estimated size of plant root system (Anderson 1988). This result indicated that plant root system played an important role in remediation of TAP. It was coincident with the previous studies. Voerman and Besemer (1975) and Singh et al. (1992) found that weak hydrophobic compounds (such as dichlorodiphenyltrichloroethane and dieldrin) were mainly accumulated in roots. Burken and Schnoor (1996) reported that hybrid poplar uptake and degradation in the rhizosphere played a major role in

Table 1 Removal kinetics constants (k) of triazophos degradation by twelve macrophytes

Species	Biomass (g)	Root/shoot ratio	Average removal kinetics constant (k) (day^{-1})
A. calamus	12.20 (0.36)*	1.37 (0.21)	0.017 (0.009)
C. indica	54.65 (0.58)	0.45 (0.10)	0.013 (0.004)
C. alternifolius	90.47 (11.22)	0.39 (0.04)	0.036 (0.012)
C. rotundus	5.31 (0.51)	1.54 (0.72)	0.033 (0.010)
E. crassipes	33.18 (1.54)	0.44 (0.28)	0.048 (0.010)
I. pseudacorus	3.43 (0.64)	0.50 (0.15)	0.042 (0.021)
P. australis	26.46 (0.95)	1.06 (0.02)	0.032 (0.004)
P. cordata	113.26 (15.36)	2.97 (3.28)	0.074 (0.048)
S. triangulates	14.20 (3.12)	0.69 (0.17)	0.036 (0.014)
T. dealbata	35.47 (3.89)	0.85 (0.17)	0.016 (0.003)
T. orientalis	121.87 (0.97)	0.69 (0.09)	0.044 (0.013)
V. zizanioides	16.23 (1.79)	0.84 (0.08)	0.031 (0.025)
Non-plant group			0.006 (0.002)

* Standard deviations are shown in parenthesis. Biomass was the average of initial and final fresh weight of plant.

phytoremediation. Fan et al. (2008) and Lee et al. (2008) showed that the microbial activity in the rhizosphere also played an important role in degradation of organic pollutants. Those reports validated the hypothesis in this study that plant root plays a key role for TAP remediation from soil or water.

Plant biomass (**Table 1**) was shown to be associated with k (R^2 = 0.379, P < 0.05) indicating that plant biomass played an important role in TAP removal. According to Karthikeyan et al. (2004), the large pool of biomass may act as a storage or sink compartment for agrochemicals Therefore, the inference can be deduced that a large biomass can accumulate more TAP, which is confirmed by other published results. Kelsey and White (2005) found a direct relationship between the total amount of *p,p′*-dichlorodiphenyldichloro-ethane (*p,p′*-DDE) taken up by plant and the biomass of plant. A general behavior was observed in the study by Garcinuno et al. (2003) that the retention efficiency of different pesticide (simazine, atrazine, isoproturon, linuron and carbaryl) increased with biomass increase.

As a result of the huge difference in those species and the interference by TAP natural degradation, k value is unsuitable to measure the TAP removal capacity of plants. According to Olette et al. (2008), the RC of plants was expressed as μg of TAP per gram of fw by day. A glaring discrepancy of RC showed among those plants (**Fig. 2**). The maximum RC of these twelve plants at 1, 3, 5 mg/L TAP occurred in *I. pseudacorus* (6.11, 52.16 and 68.05 μg/(g fw·day), respectively), which was 23–112 times higher than the minimum RC (0.26, 0.62 and 0.60 μg/(g fw·day) for *C. indica*). This results showed that the TAP removal capacity of plants is species-specific, which was consistent with former reports. Chaudhry et al. (2002) reported that the removal of pesticides by plants from water was dependent on chemical properties of the compounds, environmental conditions, initial pollutant concentration, and plant species. Huang et al. (2004) found that the contaminant tolerance and growth potential of a plant species were directly related to its biochemistry and physiology. Gao and Zhu (2004) also showed that plant uptake and accumulation of phenanthrene and pyrene were correlated with their plant composition.

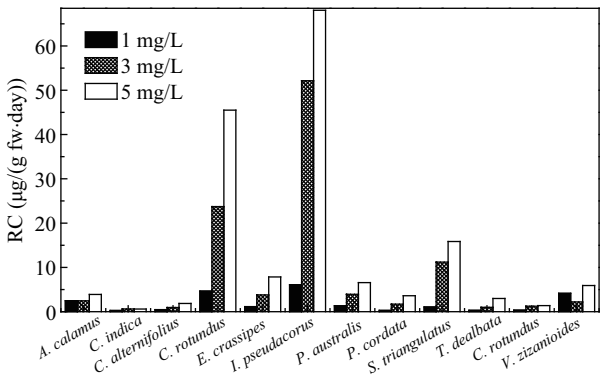


Fig. 2 Removal capacity (RC) of TAP degradation by twelve macrophytes at three concentrations of TAP.

2.3 Concentration and transportation of TAP by different macrophytes

Compounds most easily taken up by organisms are moderately hydrophobic chemicals with octanol-water partition coefficients ($\log K_{ow}$) ranging from 0.5 to 3.5 (Briggs et al., 1982). The $\log K_{ow}$ of TAP is 3.34 (Li et al., 2008), therefore, it can be absorbed and transferred easily. BCF reflects the ability of absorbing contaminants by plant. TF reflects the ability of transferring pollution from root to shoot. The average BCF and TF are shown in **Fig. 3**. The average BCFs of these plants were significantly different (P < 0.05), ranging from 0.02 (*I. pseudacorus*) to 1.17 (*A. calamus*). The average TFs of these plants were significantly different (P < 0.05), and the maximum and minimum value was 2.14 for *E. crassipes* and 0.07 for *V. zizanioides*, respectively.

The varieties of BCF and TF among the twelve plants suggested that differences existed in uptake of organics among these different plant species. Salt et al. (1998) and Olette et al. (2008) demonstrated that the difference in the capacity of plants extracting pesticide depended on plant type. The BCFs of ten plants on *p,p′*-DDE in root varied significantly (White et al., 2005). Schwab et al. (1998) indicated that lipid content of plant root was a controlling factor in the adsorption of organic matter. Gao and Zhu (2004) also demonstrated that significantly positive correlations were shown between BCF of phenanthrene and pyrene in root and root lipid contents. The low values of BCF may be related to rapid degradation of TAP *in vivo*. Our pervious study found that the concentration of TAP in plant organs absorbing during the incubation period

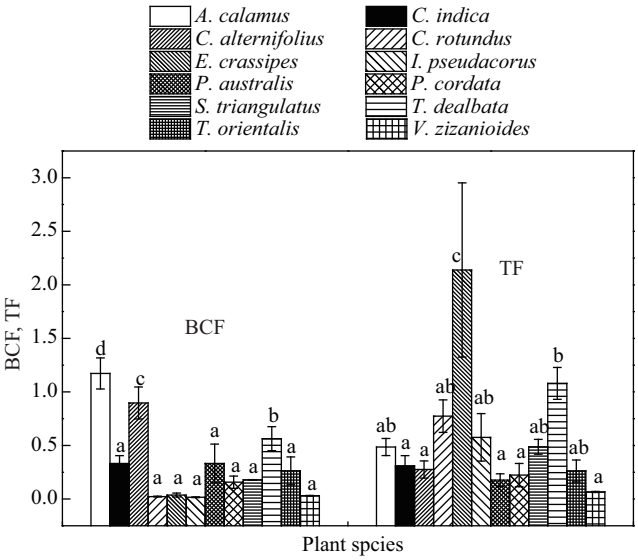


Fig. 3 Comparison of uptake and transformation ability of TAP by twelve wetland plant species. BCF: bioconcentration factor, TF: translocation factor.

decreased by 48.4%–99.9% after another 7-day cultivation in TAP-free solution (Xiao et al., 2010a).

A significant correlation was found between BCF and k value ($R^2 = 0.485$, $P < 0.01$), indicating that the absorption by plants is one major route of TAP removal in hydroponic system. BCF was also associated with root/shoot ratio ($R^2 = 0.723$, $P < 0.01$), and illustrated that developed root system could facilitate the absorption of TAP. Günther et al. (1996) reported that biodegradation of hydrocarbons in the rhizosphere was stimulated by plant roots. Therefore, the absorbing capacity of TAP and development of root system should be considered in the screening for effective plants of TAP phytoremediation. However, there was no discernible relationship between TF and k value, suggesting that the transportation ability of plants is not directly correlated to TAP removal in hydroponic system.

2.4 Comprehensive comparison on phytoremediation ability of twelve species of macrophytes

Strong tolerance and removal capacity of TAP are major features for plants in TAP phytoremediation. Owing to the reason that a single parameter is too limited to reflect the capacity of plants to remove TAP, it is necessary to comprehensively screen suitable plants for TAP phytoremediation. Combined with previous results, five plant selection principles relative to phytoremediation ability are proposed: (1) healthy growth under TAP stress, which should be a primary consideration in phytoremediation and can be reflected by RGR; (2) capacity of plants to remove TAP, which is the key factor to screen efficient plants and can be reflected by RC; (3) absorption ability of TAP, which promotes the removal of TAP and can be reflected by BCF; (4) a well-developed root system, which can stimulate biodegradation of TAP and be reflected by root/shoot ratio; (5) huge biomass, which contributes to TAP removal.

Comprehensive scores by factor analysis of those five parameters (RGR, biomass, root/shoot ratio, RCF and BCF) was used to comprehensively compare the phytoremediation ability of these plants. In the opinion of Kaiser (1974), a Kaiser-Meyer-Olkin (KMO) value greater than 0.5 is considered to be acceptable for factor analysis. The data of those parameters in this study were suitable for factor analysis, on the grounds that the KMO statistic in this study was 0.521, as well as Bartlett's test of sphericity for the adequacy was significant ($P < 0.01$). Two components were extracted and identified totaling cumulative contribution of 73.4% (**Table 2**), which could be more comprehensive to reflect the original five parameters. Component 1 occupied 48.2% of totaling cumulative contribution and mainly reflected RC, biomass and BCF; component 2 occupied 25.2% of totaling cumulative contribution and mainly reflected RGR and root/shoot ratio.

The CS of these plants are listed in **Table 3**. *C. alternifolius* had the greatest CS with 1.18 among these twelve plant species. It indicated that *C. alternifolius* owns strong ability of TAP removal and can be applied for TAP phytoremediation. In addition *A. calamus* (0.73), *T. dealbata* (0.62), *C. indica* (0.58) and *T. orientalis* (0.49) are also suitable species for their higher CS values as well.

Table 2 Rotated component matrix by factor analysis of five parameters

Index	Component	
	1	2
RC	–0.863	0
Biomass	0.763	–0.118
BCF	0.668	0.399
Root/shoot ratio	0.179	–0.890
RGR	0.612	0.725

Extraction method: principal component analysis; rotation method: varimax with Kaiser normalization.

Table 3 Comprehensive scores (CS) of twelve plants by factor analysis

Species	CS	Species	CS
C. alternifolius	1.18	*P. australis*	–0.19
A. calamus	0.73	*E. crassipes*	–0.31
T. dealbata	0.62	*P. cordata*	–0.32
C. indica	0.58	*S. triangulatus*	–0.34
T. orientalis	0.49	*I. tectorum*	–1.10
V. zizanioides	–0.09	*C. rotundus*	–1.27

* Data are in ascending order of CS values.

3 Conclusions

Phytoremediation has been proven a sound approach to remediate pesticides, including TAP. The plant specificity in ability of phytoremediation has been demonstrated. *T. dealbata*, *C. alternifolius*, *C. indica* and *A. calamus* had higher RGR values than those of other species and indicated higher tolerance under TAP stress in the hydroponic system. The higher RC loading in *I. pseudacorus* and *C. rotundus* were 42.11 and 24.63 μg/(g fw·day), respectively. The highest values of BCF occurred in *A. calamus* (1.17), TF occurred in *E. crassipes* (2.14), respectively. Biomass and root/shoot ratio of plant showed significant positive correlation with first-order kinetic constant (k) of TAP removal in the hydroponic system, indicating that plant biomass and root system play important roles in remediation of TAP.

The principles on plant selection for TAP phytoremediation are proposed: (1) healthy growth under TAP stress; (2) capacity to remove TAP; (3) absorption ability of TAP; (4) developed root system; (5) large biomass. According to factor analysis, *C. alternifolius*, *A. calamus*, *T. dealbata*, *C.*

indica and *T. orientalis*, which own higher comprehensive score, are potential species for TAP phytoremediation in contaminated water body.

Further studies are needed to understand the mechanisms of species from different families involved in TAP phytoremediation, as well as to improve the removal capacity of TAP.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 20877093, 51278355). The authors are very grateful to Dr. Weijie Guo and Dr. Hua Wei for technical assistance and Dr. Mohammed Russel for editing the manuscript.

REFERENCES

Alkorta, I., Garbisu, C., 2001. Phytoremediation of organic contaminants in soils. Bioresour. Technol. 79, 273–276.

Anderson, E. L., 1988. Tilage and N-fertilization effects on maize root growth and root:shoot ratio. Plant Soil 108, 245–251.

Blackman, V. H., 1919. The compound interest law and plant growth. Ann. Bot. 33, 353–360.

Bosch, R. V. D., Horst, M. M. S. T., Lin, C. W., Chen, Y. B., Huang, J. J., 2005. Effect of irrigation on pesticides leaching in vegetable farming in Chengdu plain using PEARL model. Ecol. Environ. 14, 710–714.

Briggs, G. G., Bromilow, R. H., Evans, A. A., 1982. Relationships between lipophilicity and root uptake and translocation of non-ionized chemicals by barley. Pesticide Sci. 13, 495–504.

Burken, J. G., Schnoor, J. L., 1996. Phytoremediation: Plant uptake of atrazine and role of root exudates. J. Environ. Engin.-Asce 122, 958–963.

Burken, J. G., Schnoor, J. L., 1997. Uptake and metabolism of atrazine by poplar trees. Environ. Sci. Technol. 31, 1399–1406.

Chaudhry, Q., Schröder, P., Werck-Reichhart, D., Grajek, W., Marecik, R., 2002. Prospects and limitations of phytoremediation for the removal of persistent pesticides in the environment. Environ. Sci. Poll. Res. 9, 4–17.

Cheng, S. P., Xiao, J., Xiao, H. P., Zhang, L. P., Wu, Z. B., 2007. Phytoremediation of triazophos by *Canna indica* Linn. in a hydroponic system. Int. J. Phytorem. 9, 453–463.

Fan, S. X., Li, P. J., Gong, Z. Q., Ren, W. X., He, N., 2008. Promotion of pyrene degradation in rhizosphere of alfalfa (*Medicago sativa* L.). Chemosphere 71, 1593–1598.

Föhse, D., Claassen, N., Jungk, A., 1988. Phosphorus efficiency of plants. Plant Soil 110, 101–109

Gao, J. P., Garrison, A. W., Hoehamer, C., Mazur, C. S., Wolfe, M. N. L., 2000a. Uptake and phytotransformation of organophosphorus pesticides by axenically cultivated aquatic plants. J. Agric. Food Chem. 48, 6114–6120.

Gao, J. P., Garrison, A. W., Hoehamer, C., Mazur, C. S., Wolfe, N. L., 2000b. Uptake and phytotransformation of *o,p′*-DDT and *p,p′*-DDT by axenically cultivated aquatic plants. J. Agric. Food Chem. 48, 6121–6127.

Gao, Y. Z., Zhu, L. Z., 2004. Plant uptake, accumulation and translocation of phenanthrene and pyrene in soils. Chemosphere 55, 1169–1178.

Garcinuno, R. M., Fernandez-Hernando, P., Camara, C., 2003. Evaluation of pesticide uptake by Lupinus seeds. Water Res. 37, 3481–3489.

Gerhardt, K. E., Huang, X. D., Glick, B. R., Greenberg, B. M., 2009. Phytoremediation and rhizoremediation of organic soil contaminants: Potential and challenges. Plant Sci. 176, 20–30.

Gui, W. J., Jin, R. Y., Chen, Z. L., Cheng, J. L., Zhu, G. N., 2006. Hapten synthesis for enzyme-linked immunoassay of the insecticide triazophos. Anal. Biochem. 357, 9–14.

Günther, T., Dornberger, U., Fritsche, W., 1996. Effects of ryegrass on biodegradation of hydrocarbons in soil. Chemosphere 33, 203–215.

Huang, X. D., El-Alawi, Y., Penrose, D. M., Glick B R, Greenberg B M, 2004. Responses of three grass species to creosote during phytoremediation. Environ. Poll. 130, 453–463.

Hutchinson, S. L., Banks, M. K., Schwab, A. P., 2001. Phytoremediation of aged petroleum sludge: Effect of inorganic fertilizer. J. Environ. Qual. 30, 395–403.

Jain, S, Ahmed, R. S., Arora, V. K., Banerjee, B. D., 2011. Biochemical and histopathological studies to assess chronic toxicity of triazophos in blood, liver and brain tissue of rats. Pesticide Biochem. Physiol. 100, 182–186.

Kaiser, H. F., 1974. An index of factorial simplicity. Pschometrika 39, 31–36.

Karthikeyan, R., Davis, L. C., Erickson, L. E., Al-Khatib, K., Kulakow, P. A., Barnes, P. L. et al., 2004. Potential for plant-based remediation of pesticide-contaminated soil and water using nontarget plants such as trees, shrubs, and grasses. Critical Rev. Plant Sci. 23, 91–101.

Kelsey, J. W., White, J. C., 2005. Multi-species interactions impact the accumulation of weathered 2,2-bis(*p*-chlorophenyl)-1,1-dichloroethylene (*p,p′*-DDE) from soil. Environ. Poll. 137, 222–230.

Lee, S. H., Lee, W. S., Lee, C. H., Kim, J. G., 2008. Degradation of phenanthrene and pyrene in rhizosphere of grasses and legumes. J. Hazard. Mater. 153, 892–898.

Li, W., Qiu, S. P., Wu, Y. J., 2008. Triazophos residues and dissipation rates in wheat crops and soil. Ecotoxicol. Environ. Safety 69, 312–316.

Naveed, A., Venkateshwarlu, P., Janaiah, C., 2010. Impact of sublethal concentration of triazophos on regulation of protein metabolism in the fish *Channa punctatus* (Bloch). African J. Biotechnol. 9, 7753–7758.

Olette, R., Couderchet, M., Biagianti, S., Eullaffroy, P., 2008. Toxicity and removal of pesticides by selected aquatic plants. Chemosphere 70, 1414–1421.

Qu, M, J., Han, Z, J., Xu, X, J., Yue, L, N., 2003. Triazophos resistance mechanisms in the rice stem borer (*Chilo suppressalis* Walker). Pesticide Biochem. Physiol. 77, 99–105.

Rani, S., Madan, V. K., Kathpal, T. S., 2001. Persistence and dissipation behavior of triazophos in canal water under Indian climatic conditions. Ecotoxicol. Environ. Safety 50, 82–84.

Salt, D. E., Smith, R. D., Raskin, I., 1998. Phytoremediation. Annu. Rev. Plant Physiol. Plant Mol. Biol. 49: 643–668.

Schwab, A. P., Al-Assi, A. A., Banks, M. K., 1998. Adsorption of naphthalene onto plant roots. J. Environ. Qual. 27, 220–224.

Singh, G., Dowman, A., Higginson, F. R., Fenton, I. G., 1992. Translocation of aged cyclodiene insecticide residues from soil into forage

crops and pastures at various growth stages under field conditions. J. Environ. Sci. Health Part B-Pesticides Food Contam. Agric. Wastes 27, 711–728.

Susarla, S., Medina, V. F., McCutcheon, S. C., 2002. Phytoremediation: An ecological solution to organic chemical contamination. Ecol. Engin. 18, 647–658.

Voerman, S., Besemer, A, F. H., 1975. Persistence of dieldrin, lindane, and DDT in a light sandy soil and their uptake by grass. Bull. Environ. Contam. Toxicol. 13, 501–505.

White, J. C., Parrish, Z. D., Isleyen, M., Gent, M, P. N., Iannucci-Berger, W., Eitzer, B. D. et al., 2005. Uptake of weathered *p,p′*-DDE by plant species effective at accumulating soil elements. Microchem. J. 81, 148–155.

Xiao, H. P., Cheng, S. P., Li, Z., Zhang, L. P., Wu, Z. B., 2010a. The fate of triazophos in a hydroponic phytoremediation system with *Canna indica* Linn. Fresenius Environ. Bull. 19, 2192–2199.

Xiao, H. P., Cheng, S. P., Wu, Z. B., 2008. Effects of pesticide triazophos on the growth and physio-biochemical characteristics of *Canna indica* Linn. J. He'nan Normal University Nat. Sci. 36, 82–85.

Xiao, H. P., Cheng, S. P., Wu, Z. B., 2010b. Microbial community variation in phytoremediation of triazophos by *Canna indica* Linn. in a hydroponic system. J. Environ. Sci. China 22, 1225–1231.

Zhang, Z. H., Yuan, Y. W., Zheng, W. R., Sun, C. X., Yang, G. L., Wang, Q., 2011. Dietary intake and its risk assessment of triazophos residue. Chinese J. Pesticide Sci. 13, 485–495.

Zhang, Z. Y., He, D. J., Xu, D. M., Liu, X. J., Hong, X. Y., 2005. A study on residual determination and degradation of triazophos in different pH water. Modern Agrochemicals 14, 25–27.

Zhong, B. J., Huang, Z. C., Lin, L., Fang, Z. H., Geng, Y., Geng, B. R., 2009. Genotoxicity of the pesticide triazophos to *Hylarana guentheri* tadpoles. Asian J. Ecotoxicol. 4, 244–250.

Editorial Board of Journal of Environmental Sciences

JOURNAL OF ENVIRONMENTAL SCIENCES

环境科学学报(英文版)

(http://www.jesc.ac.cn)

Aims and scope

Journal of Environmental Sciences is an international academic journal supervised by Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. The journal publishes original, peer-reviewed innovative research and valuable findings in environmental sciences. The types of articles published are research article, critical review, rapid communications, and special issues.

The scope of the journal embraces the treatment processes for natural groundwater, municipal, agricultural and industrial water and wastewaters; physical and chemical methods for limitation of pollutants emission into the atmospheric environment; chemical and biological and phytoremediation of contaminated soil; fate and transport of pollutants in environments; toxicological effects of terrorist chemical release on the natural environment and human health; development of environmental catalysts and materials.

For subscription to electronic edition

Elsevier is responsible for subscription of the journal. Please subscribe to the journal via http://www.elsevier.com/locate/jes.

For subscription to print edition

China: Please contact the customer service, Science Press, 16 Donghuangchenggen North Street, Beijing 100717, China. Tel: +86-10-64017032; E-mail: journal@mail.sciencep.com, or the local post office throughout China (domestic postcode: 2-580).

Outside China: Please order the journal from the Elsevier Customer Service Department at the Regional Sales Office nearest you.

Submission declaration

Submission of an article implies that the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere. The submission should be approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If the manuscript accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Submission declaration

Submission of the work described has not been published previously (except in the form of an abstract or as part of a published lecture or academic thesis), that it is not under consideration for publication elsewhere. The publication should be approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out. If the manuscript accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Editorial

Authors should submit manuscript online at http://www.jesc.ac.cn. In case of queries, please contact editorial office, Tel: +86-10-62920553, E-mail: jesc@263.net, jesc@rcees.ac.cn. Instruction to authors is available at http://www.jesc.ac.cn.

Journal of Environmental Sciences (Established in 1989)

Vol. 26 No. 2 2014

Supervised by	Chinese Academy of Sciences	**Published by**	Science Press, Beijing, China
Sponsored by	Research Center for Eco-Environmental		Elsevier Limited, The Netherlands
	Sciences, Chinese Academy of Sciences	**Distributed by**	
Edited by	Editorial Office of Journal of	Domestic	Science Press, 16 Donghuangchenggen
	Environmental Sciences		North Street, Beijing 100717, China
	P. O. Box 2871, Beijing 100085, China		Local Post Offices through China
	Tel: 86-10-62920553; http://www.jesc.ac.cn	Foreign	Elsevier Limited
	E-mail: jesc@263.net, jesc@rcees.ac.cn		http://www.elsevier.com/locate/jes
Editor-in-chief	Hongxiao Tang	**Printed by**	Beijing Beilin Printing House, 100083, China

CN 11-2629/X **Domestic postcode: 2-580** **Domestic price per issue RMB ¥ 110.00**

ISSN 1001-0742