Ecological Effectiveness of Vetiver Constructed Wetlands in Treating Oil-Refined Wastewater

Hanping Xia[1], Honghua Ke[2], Zhaoping Deng[2], Peng Tan[2], and Shizhong Liu[1]
[1]*South China Institute of Botany, Chinese Academy of Sciences, Guangzhou 510650, China*
[2]*SINOPEC Maoming Refining & Chemical Co. Ltd., Maoming 525011, Guangdong, China*

Abstract: Wastewater produced from the oil refinery of the Maoming Petro-Chemical Company, China Petro-Chemical Corporation contains high concentrations of organic and inorganic pollutants, therefore it cannot be discharged directly into river or sea unless being treated first. Four plant species, *Vetiveria zizanioides, Phragmites australis*, *Typha latifolia*, and *Lepironia articutala* were planted in large containers as a vertical flow wetland to test their efficiencies in the purification of oil refined wastewater and their growth in wetlands soaked with oil refined wastewater. The results from a 2-month treatment indicated that the purifying rates of constructed wetlands for oil-refined wastewater were all very high at the beginning. Results included the removal of 97.7% of ammonia N, 78.2% of COD, 91.4% of BOD, and 95.3% of oil in the first batch of highly-concentrated wastewater (HCW), and 97.1% of ammonia N, 71.5% of COD, 73.7% of BOD, and 89.8% of oil in the first batch of low-concentrated wastewater (LCW). The performance of wetlands however was decreased and became basically stable as time passed. The efficiency of wetlands in removing the pollutants was always in order of ammonia N > oil > BOD > COD, but the net removal from plants was ranked as COD > BOD > oil and ammonia N. In the beginning, the purifying function of plants was quite weak, but it gradually increased with the acceleration of plants growth. However, there was almost no significant difference in the removal efficiencies among the four species. The four tested species produced better growth in wetlands (HCW or LCW) than with clean water, but *V. zizanioides*, *P. australis*, *T. latifolia* produced fewer tillers in HCW than those in LCW, while this was contrary to *L. articutala*. This could infer HCW might damage the first three species, and promote the growth of *L. articutala* During the period of clean water cultivation before the start of the trial, the new tiller producing rate of *V. zizanioides* was the lowest among the four species, but it gradually rose during the period of water soak treatment, while the tiller-producing rates of the other three species were distinctly lowered. It was therefore suggested that *V. zizanioides* might have a stronger adaptation to the harsh environment than other species tested in the experiment, especially in the situation of long time of adaptation to the environment. However, the above results remains to be further verified due to the limited observation time of only two months.

Key words: constructed wetland, wastewater treatment, phyto-remediation, oil-refined wastewater

Email contact: Hanping Xia <xiahanp@scib.ac.cn>

1 INTRODUCTION

Water is the source of life, and is the basic condition of human survival. Severe water pollution and insufficient supply are two difficult problems facing the water environment around the globe. In China, the water problem is more prominent and urgent. There is only 2500 m^3 water resource per capita in China, less than one-fourth of the world's average. In 1999, the total wastewater discharge amount in China was 40.1 billion tons, and COD in the wastewater was 13.9 million tons, but the treatment rate was only 29.65%. As a result, about 80% of waters, including 45% of ground water and 90% of cities'

Guangdong is one of the most developed provinces in China, but its pollution, especially industrial pollution, is also quite severe. For example, the Maoming Petro-Chemical Company (MPCC), China Petro-Chemical Corporation in Southwest Guangdong, discharged 13.12 million tons of oil-refined wastewater and 7.48 million tons of ethylene-produced wastewater in the year 1999 alone. The company has strongly recognized the importance of environmental protection, and invested substantially in building new purifying plants and in enlarging the capacity of old plants. However, only 63.4% of oil-refined wastewater reached the effluent standard in 1999, indicating that the company still has a major task with special reference to wastewater purification.

Wetlands are regarded as very effective in the field of environmental protection, especially for wastewater treatment. For example, Knight *et al.*, through statistic calculation using a data set 1300 showed that the mean purifying rates of constructed wetlands for livestock wastewater were 65% for BOD, 53% for TSS, 48% for NH_4-N, 42% for TN, and 42% for TP (Knight *et al.*, 2000). Due to its low expense, low energy-consumption, high effectiveness and sustainability, wetland treatment systems are regarded as a promising wastewater-treating technique, and are being used by more and more countries and regions, particularly by developing nations (Dunbabin and Bowmer, 1992; Kivaisi, 2001; Xia, 2002). Constructed wetlands also have been used to treat petroleum industry effluents, but they are still concentrated mainly on the remove of COD, suspended solids, and heavy metals (Knight et al., 1999). There has been very poor documentation to date on the purification of constructed wetlands for the main pollutants of petroleum industry effluents, such as oil, phenol, and benzene.

Many experiments and observations have confirmed that vetiver grass Vetiveria zizanioides has excellent effects in erosion control, amelioration of harsh soil conditions, wastewater purification, and other environmental uses (Kantawanichkul et al., 1999; Truong and Hart, 2001; Xia and Shu, 2001). For example, vetiver established in wetland could effectively remove extra solids and nutrients in aquaculture sludge, and the removal rates to suspended solids, total COD, total kjeldahl N, total P, and dissolved P were 96–98%, 72–91%, 86–89%, 82–90%, and 92–93%, respectively (Summerfelt *et al.*, 1999). This species can also purify over 87% of ammonia N and 74% of total P from landfill leachate (Xia *et al.*, 2002). *Phragmites australia* (Cav.) Trin. ex Steudel and *Typha latifolia* L., the two common species in South China as well as in tropical and subtropical regions of the globe, have also been proved to be highly effective in pollutant removal (Taylor and Growder, 1984; Li and Hu, 1995; Kern and Idler, 1999; Ye *et al.*, 2001). *Lepironia articutala* Rich., a local species of South China and a potential pollutant-purifying plant, grows mainly on natural wetlands nearby mine tailings or industrially polluted areas, but there has been no any report on its effectiveness for wastewater purification. In general, there are very few documents on the purification of wetland systems using the four above species for industrial wastewater, especially oil-refined wastewater. It is hoped, therefore, that the present study would provide information, firstly to demonstrate the ability of the four plants in purifying wastewater from oil refinery by using constructed wetlands, secondly to screen out the highly effective pollutant removing species, and thirdly to offer an economical and effective pollutant purifying method for industrial wastewater, especially for oil-refined wastewater.

2 MATERIALS AND METHODS

2.1_ Experimental Materials

The experiment was set up at the wastewater treatment station of MPCC, and simulated constructed wetlands were used in this experiment. The soil used in the wetlands was dug from a local nursery; it is sandy loamy soil, and its chemical features are listed below (Table 1).

Table 1_Chemical characteristics of soil used in constructed wetlands

pH	Organic matter (g/kg)	Total N (g/kg)	Total P (g/kg)	Total K (g/kg)	Total S (g/kg)	Available N (mg/kg)	Available P (mg/kg)	Available K (mg/kg)
4.57	6.10	0.33	0.14	4.48	0.11	30.0	12.7	74.7

The tested wastewater in the trial consisted of a highly concentrated wastewater (HCW) and a low concentrated wastewater (LCW). The former was the flotation wastewater, having the highest concentration of pollutants; the latter was HCW after having been physically and chemically treated. Of the tested 4 herbaceous species, *V. zizanioides*, *P. australis*, and *T. latifolia* were collected from the nursery of South China Institute of Botany (SCIB), the first had been growing in the xeric environment, and the latter two in the hydrophytic one. *L. articutala* was collected from a natural wastewater discharging channel beside the oil-shale waste dump in Maoming, which had very similar characteristics to an artificial wetland used for wastewater purification.

2.2_ Trial Designs and Arrangements

Simulated artificial wetlands were constructed in large earthen containers, filled with wastewater for purification. Three water treatments (HCW, LCW, and clean water (CW)) and 4 plant treatments (*V. zizanioides*, *P. australis*, *T. latifolia*, and *L. articutala*) were used. In addition, 2 controls were included in the trial, which were HCW wetland without plants and LCW wetland without plants. All treatments and controls had three replicates. During the trial period all the containers were grown in open air under a frame which was covered by a large cloth canopy to prevent rainwater from entering the containers.

Large earthen containers, 70 cm high and 90 cm in diameter, with an outlet drain for each one on the bottom were custom-made for the trial. Each container was then filled with 87.1 kg (DW) of soil and then was planted with 18 slips of one of the above 4 species. Due to the big differences of stem diameter among different species, *T. latifolia*, *P. australis*, *V. zizanioides*, and *L. articutala* were planted with 1 tiller, 2, 3, and 5 tillers, respectively, in order to make each species have a similar biomass at planting. Prior to planting, their tops and roots were all pruned to 30 cm and 5 cm, respectively. After planting, clean water was loaded into the pots until the water level was 10 cm higher than the soil surface. The survival rates were recorded and dead slips were replaced after 15 days. During the period of establishment, clean water was added to the containers once every 2–4 days to supplement water loss by evapo-transpiration. At the end of the 2 months establishment period, the soil was let to dry out. Then the 3 treatment waters were loaded, 55 kg for each container. Samples of wastewater were collected from the drains for chemical analysis 8 days after loading. After each test all wastewaters were discharged and containers were left open until the soil become almost dry, then the second and third batches of wastewater were loaded, and the same operation as the first batch was repeated 8 days after each batch of wastewaters was loaded. The three batches of wastewaters lasted in constructed wetlands from July 17th–25th, August 6th–14th, August 21st–29th, respectively. Obviously, the experiment can be divided into two stages: the stage of clean water cultivation, which was from May 4th to July 16th; and the stage of treatment water cultivation, which was from July 17th to September 9th.

2.3_ Observations and Analysis

2.3.1_*Plant growth in wetlands*

The observation included the survival rate, plant height and tiller number. The latter two observations were made twice, which were prior to loading treatment water (July 16) and in the end of the experiment (September 9), respectively.

2.3.2_*Analyses of wastewater*

The analyses included pH, ammonia nitrogen (AN), oil, sulfide, volatile phenol (VP), benzene, COD, and BOD. pH was measured with a pH meter. COD values were measured through measuring the consumption of dissolved oxygen while the wastewaters were oxidized with $KMnO_4$; BOD was also referred to as the consumption of dissolved oxygen after the wastewaters were incubated 5 days at 20_ in an incubator. Ammonia N was determined with direct distillation; VP and sulfide were measured by colorimetry; oil was determined by ultraviolet spectrophotometry, and benzene by gas chromatography.

3 RESULTS AND DISCUSSION

3.1_Quality of Wastewaters at Loading Time and Purifying Efficiency of the Physical and Chemical Method

The levels of AN, COD, BOD, oil, VP, and benzene in wastewaters before (HCW) and after (LCW) being treated by the physical and chemical methods at the wastewater treatment plant are listed in Table 2. It showed that the concentrations of these pollutants, except for pH and sulfide, in HCW, were almost all higher than the Second Grade Standard (SGD) of Wastewater Discharge Limits (WDL) in Guangdong (DB44/26–2001). After HCW was physically and chemically treated, the contents of these pollutants in LCW significantly decreased, and almost all of them reached SGD with the exception of AN and oil in the second batch; some of them, such as BOD, VP, and benzene were even lower than the First Grade Standard. This indicated that the physical and chemical purifying efficiencies were good, from the lowest, round 30% for AN to the highest, nearly 100% for benzene (Table 2). Considering that acidity and sulfide in HCW met the discharge standard, and VP and benzene were almost all removed by the physical and chemical methods in the first and second analyses, these four pollutants were not measured any longer in the third analysis. In addition, it can be seen from Table 2 that the water quality of wastewaters is quite changeable and the physical and chemical removal rates are also unstable. For example, VP in HCW was 1.8 mg/L in the first batch and become into 8.48 mg/L in the second, increasing by nearly 4 times. BOD and other pollutants had the similar changes.

Table 2_Quality of wastewaters at the different loading stages[a]

Wastewater type	pH	AN	COD	BOD	Oil	Sulfide	VP	Benzene
Water quality of the first batch of wastewaters at the time of loading (17 July 2002)								
HCW	7.10	22	132	41	36	0.18	1.80	8.972
LCW	7.22	17	87	8.2	6.0	0.08	0.07	0.005
Purifying rate[b] (%)	/	22.7	34.1	80.0	83.3	55.5	96.1	>99.9
Water quality of the second batch of wastewaters at the time of loading (6 August 2002)								
HCW	7.21	29	196	26	47	0.46	8.48	9.30
LCW	7.02	18	67	6.7	13	0.05	0.05	0.005
Purifying rate (%)	/	37.9	65.8	74.2	72.3	89.1	99.3	>99.9
Water quality of the third batch of wastewaters at the time of loading (21 August 2002)								
HCW	/	50	174	78	61	/	/	/
LCW	/	34	78	9.2	5.4	/	/	/
Purifying rate (%)	/	32.0	55.2	88.2	91.1	/	/	/
Wastewater Discharge Limits in Guangdong Province, China (DB44/26–2001)[c]								
Second grade	6–9	15	120	30	8	1.0	0.5	2.5
First grade	6–9	10	60	20	5	0.5	0.3	2.0

[a] The unit of all data is mg/L; 0.005 is the instrument measuring lowest limit of benzene.

[c] Issued by Guangdong Provincial Bureau of Environmental Protection on 20 August 2001

3.2_ Purifying Benefits of Constructed Wetlands in the First Batch of Wastewaters

The quality of the first batch of wastewaters after being treated in wetlands for 8 days is shown in Table 3, which indicated that: 1) apart from a small rise in pH, all other pollutants dropped sharply, and furthermore AN, VP, and benzene all reached the instrument measuring lowest limits, and parts of BOD and sulfide also reached their respective lowest limits; 2) comparing HCW with LCW, the drop of pollutant levels was higher in the former than in the latter; and 3) the purifying rates of wetlands were all in the order of AN > oil > BOD > COD, irrespective of the type of wastewaters, LCW or HCW. The reasons for the highest purifying rate for AN were probably due both to its strong volatility and the easy transformation feature into nitrate N or N_2 (Xia *et al.*, 2002). Kantawanichkul *et al.* (1999) also found that TKN and NH_3-N was removed over 90% by constructed wetlands with *V. zizanioides.* It is interesting that the removal of AN was the lowest by using the physical and chemical method (Table 2), whereas it was the highest by wetland systems (Table 3). The removal rates of oil by constructed wetlands were also quite high, up to 89.8% in LCW and 95.3% in HCW. Ji *et al*, measured removal efficiencies of reed beds to mineral oil were 88–96% (Ji *et al.*, 2002). Another phenomenon in Table 3 shows that treatments with plants had the almost the same purifying efficiencies as those without plants (controls), which is revealed more clearly in Table 4.

Table 3_Quality of the first batch of wastewaters after 8 days treatment in wetlands*

Treatment	pH	AN	COD	BOD	Oil	Sulfide	VP	Benzene
Water quality and removal rates of HCW								
CK	8.51±0.16	0.5 (97.7)	32.1±4.4 (75.8)	4.1±0.7 (90.0)	1.80±0.09 (95.0)	0.11 (38.9)	0.02	0.005
V. zizanioides	7.57±0.05	0.5 (97.7)	30.9±5.9 (76.5)	4.4±1.1 (89.3)	1.30±0.37 (96.4)	0.11 (38.9)	0.02	0.005
T. latifolia	7.92±0.09	0.5 (97.7)	26.4±6.6 (80.3)	3.8±0.8 (90.7)	2.40±0.10 (93.3)	0.01 (94.4)	0.02	0.005
P. australis	7.86±0.18	0.5 (97.7)	31.7±1.1 (75.8)	3.3±0.4 (91.9)	0.85±0.07 (97.6)	0.03 (83.3)	0.02	0.005
L. articutala	7.82±0.15	0.5 (97.7)	23.5±3.3 (82.6)	2.0 (95.1)	2.10±0.15 (94.2)	0.07 (61.1)	0.02	0.005
Mean purifying rate (%)		97.7	78.2	91.4	95.3	63.3	/	/
Water quality and removal rates of LCW								
CK	8.10±0.05	0.5 (97.1)	26.0±5.4 (70.1)	2.8±0.1 (65.9)	0.55±0.02 (90.8)	0.02 (75.0)	0.02	0.005
V. zizanioides	7.82±0.22	0.5 (97.1)	28.5±2.7 (66.7)	2.0 (75.6)	0.93±0.07 (84.5)	0.02 (75.0)	0.02	0.005
T. latifolia	7.96±0.27	0.5 (97.1)	24.6±2.0 (71.3)	2.0 (75.6)	0.77±0.10 (87.2)	0.01 (87.5)	0.02	0.005
P. australis,	7.59±0.11	0.5 (97.1)	27.7±1.4 (67.8)	2.0 (75.6)	0.31±0.02 (94.8)	0.02 (75.0)	0.02	0.005
L. articutala	7.88±0.11	0.5 (97.1)	16.4±4.2 (81.6)	2.0 (75.6)	0.51±0.03 (91.5)	0.02 (75.0)	0.02	0.005
Mean purifying rate (%)		97.1	71.5	73.7	89.8	77.5	/	/

[a] The units of all observed data (parts are means ± SD) are the same as those in Table 2; data in parentheses are purifying rates (%); mean purifying rate is the average value of purifying rates in each column; 0.5, 2.0, 0.01, 0.02, and 0.005 are the instrument measuring lowest limits of AN, BOD, sulfide, VP, and benzene, respectively. When the measured data are smaller than the instrument measuring lowest limits, they are treated as the instrument measuring lowest limits.

The effectiveness of plants for pollutant purification in the present experiment was not so distinct in the beginning of the experiment (Table 4). The net purified amounts coming from plants were very low, and some of them were even negative, namely the purifying effectiveness of the treatments with plants was even poorer than controls. This was probably due to the relatively smaller biomass and the relatively poorer adaptation to the wastewater environment at the beginning. Table 4 also shows that there were almost no significant differences among different species with regard to their purifying efficiencies to pollutants, except for parts of COD (P>0.05). Overall the purifying effectiveness of *L. articutala* was slightly better compared with other 3 species.

Table 4_The net removal of COD, BOD and oil by plants in the first batch of wastewaters*

Treatment	Species	COD	BOD	Oil
HCW	*V. zizanioides*	1.2	-0.3	0.50
	T. latifolia	5.7	0.3	-0.60
	P. australis	0.4	0.8	0.95
	L. articutala	8.6	2.1	-0.30
LCW	*V. zizanioides*	-2.5	0.8	-0.38
	T. latifolia	1.4	0.8	-0.22
	P. australis	-1.3	0.8	0.24
	L. articutala	9.6	0.8	0.04

*Concentrations are expressed by mg/L; "-" indicates an increase of pollutants after being "purified" by plants

3.3_ Purifying Benefits of Constructed Wetlands in the Second Batch of Wastewater

The second batch of wastewaters was loaded after the first batch was discharged for 11 days, and then samples were collected for analysis 8 days later (Table 5). The changes of concentrations were basically consistent with the first batch. 1) pH values slightly increased. 2) All pollutants decreased at varying degrees, among them VP and benzene of all treatments went down to their respective instrument measuring lowest limits, so did parts of AN and sulfide. This further indicates that wetlands provided very high removal rates of these pollutants, the highest of which was benzene in HCW, up to over 99%. 3) The removal rates of wetlands to AN, COD, BOD and oil still presented in order of AN > oil > BOD > COD. 4) Most purifying rates of this batch were lower in comparison with those of the first batch, but those in LCW had a higher reduction rate, especially COD, which dropped to 35.8%. This is perhaps because the purifying ability of wetlands decreases with age. 5) Overall purifying effectiveness of wetlands to high concentration pollutants (in HCW) was better than to low concentration pollutants (in LCW), except for AN. 6) Purifying efficiency of plants still was not very high, namely the difference of purifying rates was very small between treatments with plants and without plants (CK).

3.4_ Purifying Benefits of Constructed Wetlands in the Third Batch of Wastewater

The third batch of wastewaters was loaded after the second batch of wastewater was discharged for 7 days. The results of water quality and purifying efficiencies 8 days after staying in wetlands are presented in Table 7. The purifying abilities of wetlands to the 4 pollutants were still ranked as AN > oil > BOD > COD, further inferring that AN was one of the most easily bio-removed elements from wastewater while COD was one of the hardest bio-removed elements. In comparison to the purifying rates of the second batch, those of the third batch did not have a clear increase or decrease, suggesting that wetlands began to enter a relatively stable state. In general, the purifying rates of the third batch of effect of HCW by wetlands was higher than that of LCW similar to the first two batches of wastewater.

Table 5_Quality of the second batch of wastewaters after 8 days treatment in wetlands*

Treatment	pH	AN	COD	BOD	Oil	Sulfide	VP	Benzene
Water quality and removal rates of HCW								
CK	8.65±0.06	2.9±0.1 (90.0)	65.9±8.8 (66.3)	9.8±0.7 (62.3)	3.53±0.08 (92.6)	0.04 (91.3)	0.02	0.005
V. zizanioides	7.70±0.10	1.5±0.3 (94.8)	49.4±6.6 (75.0)	6.7±1.1 (74.1)	2.22±0.34 (95.3)	0.02 (95.7)	0.02	0.005
T. latifolia	8.02±0.25	2.1±0.4 (92.8)	58.6±2.3 (69.9)	7.9±1.0 (69.7)	2.37±0.31 (94.9)	0.04 (91.3)	0.02	0.005
P. australis	7.83±0.11	1.3±0.1 (95.5)	53.3±5.0 (73.0)	5.7±0.2 (77.9)	2.90±0.07 (93.8)	0.03 (93.5)	0.02	0.005
L. articutala	7.98±0.34	0.9±0.1 (96.9)	50.1±8.3 (74.5)	2.9±0.4 (89.0)	2.40±0.15 (94.9)	0.04 (91.3)	0.02	0.005
Mean purifying rate (%)		94.0	71.7	84.6	94.3	92.6	/	/
Water quality and removal rates of LCW								
CK	8.12±0.11	1.3±0.3 (92.8)	40.6±7.0 (38.8)	2.1±0.1 (68.7)	2.44±0.20 (81.5)	0.01 (80.0)	0.02	0.005
V. zizanioides	7.95±0.20	0.5 (97.2)	43.6±2.9 (34.3)	2.0 (70.1)	1.59±0.4.3 (87.7)	0.01 (80.0)	0.02	0.005
T. latifolia	8.14±0.07	0.5 (97.2)	49.5±0.9 (25.4)	3.2±0.2 (52.2)	1.61±0.33 (87.7)	0.01 (80.0)	0.02	0.005
P. australis,	7.78±0.05	1.3±0.4 (92.8)	45.2±4.7 (32.8)	2.4±0.1 (64.2)	1.68±0.08 (86.9)	0.01 (80.0)	0.02	0.005
L. articutala	8.20±0.10	0.5 (97.2)	35.2±3.5 (47.8)	2.6±0.4 (61.2)	1.85±0.13 (85.4)	0.01 (80.0)	0.02	0.005
Mean purifying rate (%)		95.4	35.8	63.3	85.8	80.0	/	/

*The units of all observed data are the same as Table 2, and others have the same meanings as Table 3.

Table 6 showed that the net removing amounts of treatments with plants to AN, COD, BOD and oil in HCW were all positive values, indicating that plants began to produce purifying efficiency to these pollutants in the second batch of wastewaters. This result also suggests that wetlands with plants were more effective in treating HCW than LCW, because the net removing amounts to pollutants in LCW were lower, close to 0 or even negative. This inferred that the purifying ability of plants were still unstable at this stage. Regarding the purifying effectiveness among different species, it was still *L. articutala*, which performed slightly better than *V. zizanioides*, *P. Australia*, and *T. latifolia.* On the whole, the purifying abilities of the four species to wastewater did not assume a big difference.

Table 6 The net removal of AN, COD, BOD and oil by plants in the second batch of wastewaters*

Treatment	Species	AN	COD	BOD	Oil
HCW	*V. zizanioides*	1.4	16.5	3.1	1.31
	T. latifolia	0.8	7.3	1.9	1.16
	P. australis	1.6	12.6	4.1	0.63
	L. articutala	2.0	15.8	6.9	1.13
LCW	*V. zizanioides*	0.8	-3.0	0.1	0.85
	T. latifolia	0.8	-8.9	-1.1	0.83
	P. australis	0	4.6	0.3	0.77

	L. articutala	0.8	5.4	-0.5	0.59

*The data are expressed with mg/L. "-" indicates an increase of pollutants after being "purified" by plants

Table 7_Quality of the third batch of wastewaters after 8 days treatment in wetlands*

Wastewater type	Treatment	AN	COD	BOD	Oil	Mean purifying rate (%)
HCW	CK	2.2±0.2 (95.6)	81.3±4.0 (53.3)	8.7±1.7 (88.8)	3.10±0.13 (94.9)	83.2
	V. zizanioides	1.1±0.1 (97.9)	63.7±7.9 (63.4)	5.6±0.3 (92.8)	2.85±0.56 (95.2)	87.3
	T. latifolia	1.1±0.3 (97.8)	51.0±5.8 (70.7)	4.1±0.7 (94.7)	2.13±0.07 (96.6)	89.9
	P. australis	1.2±0.4 (97.7)	53.7±2.1 (69.2)	5.1±0.7 (93.4)	1.89±0.89 (96.9)	89.3
	L. articutala	1.1±0.2 (97.7)	61.3±5.0 (64.8)	5.2±0.8 (93.3)	2.35±0.44 (96.2)	88.0
Mean purifying rate (%)		97.3	64.3	92.6	96.0	87.5
LCW	CK	0.7±0.1 (98.0)	59.7±1.4 (23.5)	4.9±0.3 (46.4)	2.03±0.04 (63.0)	57.7
	V. zizanioides	0.5 (98.5)	45.7±3.6 (41.4)	2.3±0.3 (74.6)	1.67±0.04 (68.5)	70.7
	T. latifolia	0.5 (98.5)	40.0±1.0 (48.7)	2.5±0.4 (72.5)	1.25±0.77 (77.0)	74.2
	P. australis	0.5 (98.5)	43.0±8.8 (44.9)	2.3±0.1 (75.0)	1.52±0.44 (71.5)	72.5
	L. articutala	0.5 (98.5)	47.7±7.8 (38.9)	2.4±0.1 (74.3)	1.30±0.09 (75.3)	71.8
Mean purifying rate (%)		98.4	39.6	68. 6	71.1	69.5

*The units of all observed data are the same as Table 2, and others have the same meanings as Table 3

Regarding the net purifying ability of plants, the four species began to produce net removing rates to all pollutants in both types of wastewaters (Table 8). Furthermore, the removed amounts of the four elements were COD > BOD > oil and AN, which was completely contrary to the order of their removal rates by wetlands (Table 3, 5, and 7). Combined with purification of plants in the first two batches of wastewater, it was found that the purifying capacity of plants in wetland systems gradually increased with wetland's age. This was obviously associated with gradual growth and development of the plants resulting in a gradual increase of biomass, and also they gradually adapted themselves to the wastewater environment as they grew in wetlands. It is positive, therefore, that the purifying ability of plants in wetlands became stronger and stronger as plants grew. In addition, there still was no clear distinction of the purifying benefits among the 4 species to same pollutant or same species to different pollutants. On the whole, the effectiveness of *T. latifolia* was best, *L. articutala* was second, and *P. australia* and *V. zizanioides* were last. It was suggested, therefore, that wetland covered by several plant species might be superior to that by single species with reference to removal efficiency of pollutants.

Table 8_The net removal of AN, COD, BOD and oil by plants in the third batch of wastewaters*

Wastewater type	Species	AN	COD	BOD	Oil
HCW	*V. zizanioides*	1.2	17.6	3.1	0.2
	T. latifolia	1.1	30.3	4.6	1.0
	P. australis	1.0	27.6	3.6	1.2
	L. articutala	1.1	20.0	3.5	0.8
LCW	*V. zizanioides*	0.2	14.0	2.6	0.3

P. australis	0.2	16.7	2.6	0.5
L. articutala	0.2	12.0	2.5	0.7

*Concentrations are expressed in mg/L

3.5_ Survival and Growth of Plants in Wetlands

On the 15th day after planting, the survival rates were investigated, 100% were recorded for *V. zizanioides*, *P. australis*, and *L. articutala*, but only 91.3% for *T. latifolia*, indicating the last species was difficult to transplant. In terms of growth, the four species all grew better in wetlands with two types of wastewater than in those with clear water in terms of plant height and tiller number (Table 9). This was probably due to the presence of some nutrients in wastewater. It was also found from Table 9 that *V. zizanioides*, *P. australis*, and *T. latifolia* produced less growth in HCW than in LCW, particularly their tiller numbers. This is perhaps because that HCW contained higher levels of phyto-toxic materials to the three species than LCW. *L. articutala* was different, it grew better in HCW than in LCW, inferring that this species might be more tolerant to pollution than the other 3 species. Considering the original habitats of the four species, *V. zizanioides*, *P. australis*, and *T. latifolia* were taken from the nursery of SCIB under a good habitat condition, whereas *L. articutala* was from a leachate-discharging wetland near the oil shale residue dump where it established naturally. Therefore *L. articutala* original habitat was closest to that of the experiment, and probably due to this reason that *L. articutala* grew better than other three species. Moreover, the stronger removing efficiency of *L. articutala* as shown in Table 4 and 6 was probably also due to this reason. Many plants can assume adaptive tolerance, meaning that plants generally produce or increase tolerance to one harsh environment after growing for some time in the special environment (Taylor and Growder, 1984; Mcnaughton, *et al*., 1974). For example, *T. latifolia* from metal-contaminated sites accumulates considerably more metals, up to nearly twice as much Zn and Pb and three times as much Cd, in roots than those from the uncontaminated sites (Ye *et al*., 1997).

Table 9_Growth of the four plants tested in constructed wetlands

Species	Water treatment	First investigation (July 16th)		Second investigation (Sep. 9th)	
		Plant height (cm)	Number of tillers (No./clump)	Plant height (cm)	Number of tillers (No./clump)
V. zizanioides	CW	102.9±10.9	4.5±1.4	110.7±9.8	5.4±1.5
	LCW	104.3±8.7	4.7±1.9	136.8±8.5	8.8±2.5
	HCW	104.5±7.0	4.9±2.2	136.9±10.5	8.4±3.1
T. latifolia	CW	84.7±9.2	3.4±1.5	120.2±17.3	4.3±2.0
	LCW	83.3±13.3	3.3±1.0	133.2±19.2	6.2±2.0
	HCW	84.6±11.6	3.6±1.3	125.8±19.3	5.8±2.5
P. australis	CW	81.8±16.2	4.2±1.4	87.7±17.9	4.9±2.1
	LCW	74.3±12.7	3.9±2.0	106.3±18.5	6.4±3.0
	HCW	82.1±10.3	4.3±1.3	113.1±10.8	6.3±3.5
L. articutala	CW	82.2±4.4	15.9±4.1	101.9±9.0	17.7±5.9
	LCW	81.1±7.0	17.3±4.1	126.7±7.7	28.8±7.6
	HCW	86.1±6.1	16.9±3.4	129.8±6.5	33.3±7.8

The tillering rate is the ratio of tiller number observed in the last time to the current number (Xia *et al.*, 1994). The tiller numbers of each slip of *V. zizanioides*, *P. australis*, *T. latifolia*, and *L. articutala*,were 3, 2, 1, and 5, respectively at the time of planting. And then combined with Table 9, the tillering rates of the four grasses in different stages, clean water cultivation and treatment water cultivation stages, are calculated in Table 10. At the establishment stage in clean water, the tillering rate of *V. zizanioides* was the lowest, inferring it was affected negatively by the change of habitat from the xeric to hydrophytic environment. The slow growth of *V. zizanioides* in the beginning could be explained by the gradual wetland conditions (Liao, 2000). The other three species were all collected from hydorphytic habitat, as a result they were hardly influenced by the wetlands environment. At the treatment water phase, the tillering rates of *P. australis*, *T. latifolia*, and *L. articutala* tangibly decreased, whereas those of *V. zizanioides* increased. This revealed that *V. zizanioides* could acclimatize itself to the hydrophytic environment after it was transferred to the new one. This was probably because that the size and number of air chambers in the leaves of *V. zizanioides* gradually became larger, and furthermore air chambers accumulated ergastic substance when it was transplanted from dryland to wetland (Liao, 2000). Ergastic substance is possibly related to the storage of contaminants from the wetland. Once adapted, *V. zizanioides* can produce quite rapid tiller forming rate even it is in wastewater. It might be inferred, thereby, that the tillering speed of *V. zizanioides* would become faster and faster relative to other three species as it matures although it is not a hydrophyte as the other three species.

Table 10 Tillering rates of the four plants before and after wastewater irrigation

Stage	*V. zizanioides*			*P. australia*			*T. latifolia*			*L. articutala*		
	CW	LCW	HCW	CW	LCW	HCW	CW	LCW	HCW	CW	LCW	HCW
Clean water stage	1.50	1.57	1.63	2.10	1.95	1.70	3.40	3.30	3.60	3.18	3.46	3.38
Treatment water stage	1.20	1.87	1.71	1.17	1.64	1.47	1.26	1.88	1.61	1.11	1.66	1.97

4 CONCLUSION

It might be concluded from the foregoing results:

1) The concentrations of pollutants in oil-refined wastewater were quite high, especially in HCW; they exceeded the second grade of WDL in Guangdong, China. The tested indices of LCW that came from HCW after physical and chemical purification, almost all met WDL.

2) In general, the pollutants removal rates of physical and chemical methods for oil-refined wastewater were high despite the continuously changing concentrations of the pollutants and the relatively unstable removal efficiencies.

3) In the beginning, the wetlands could remove almost all pollutants in wastewaters, but their efficiencies became slower and then became relatively stable with time. The purifying efficiencies of wetland were in order of AN > oil > BOD > COD.

4) At the start of the trial the purifying function of plants was quite weak. As time passed, however, the function of plants gradually increased with acceleration of plant growth and increase of biomass. But there were only small variations among purifying abilities of different species. The net removed amounts of plants to pollutants ranked as COD > BOD >oil and AN.

5) All tested species, *V. zizanioides*, *P. australis*, *T. latifolia*, and *L. articutala* had better growth in wetlands with any type of wastewaters than in wetlands with clean water. However, the tiller numbers of the first three species in HCW were fewer than those in LCW, except for *L. articutala*, This result was perhaps related to the natural habitat of *L. articutala*, which was a natural effluent wetland of oil-shale waste dump in the locality and very similar to the habitat of the experiment; whereas the other three species were collected from the nursery having different growing conditions.

6) During the phase of clean water cultivation, the tiller producing rate of *V. zizanioides* was lowest among the four species. This was also associated probably with their original habitats, as *V. zizanioides* was sampled from the xeric environment while other three species were from the hydrophytic one. During the phase of treatment water cultivation, *V. zizanioides* possesses stronger tiller-producing ability than the other three species after it has acclimatized itself to the hydrophytic environment.

Acknowledgments

This study was supported by the William F. Donner Foundation through The Vetiver Network, SINOPEC Maoming Refining & Chemical Co. Ltd., and Guangdong NSF Group Project (003031). Thanks are also due to Dr. Paul Truong, the principal soil conservationist of Resource Science Centre, Department of Nature Resources, Queensland, Australia for his complete corrections and review to the paper.

References

Dunbabin JS, and Bowmer KH. 1992. Potential use of constructed wetlands for treatment of industrial wastewaters containing metals. Science of the Total Environment, 111: 151–168

Ji GD, Sun TH, Sun X, *et al.* 2002. Impact of ground crude oil on the ecological engineering purification system of reed wetland. Acta Ecologica Sinica, 22: 649–654

Kantawanichkul S, Pilaila S, Tanapiyawanich W, *et al.* 1999. Wastewater treatment by tropical plants in vertical-flow constructed wetlands. Water Science and Technology, 40(3): 173–178

Kern J, and Idler C. 1999. Treatment of domestic and agricultural wastewater by reed bed systems. Ecological Engineering, 12: 13–25

Kivaisi AK. 2001. The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review. Ecological Engineering, 16: 545–560

Knight RL, Kadlec RH, and Ohlendorf HM. 1999. The use of treatment wetlands for petroleum industry effluents. Environmental Science & Technology, 33: 973–980

Knight RL, Payne Jr VWE, Borer RE, *et al*. 2000. Constructed wetlands for livestock wastewater management. Ecological Engineering, 15: 41–55

Li KD, and Hu ZG. 1995. Mechanisms of sewage purification by reed bed system. China Environmental Science, 15(2): 140–144

Liao XD. 2000. Studies on Plant Ecology and System Mechanisms of Constructed Wetlands for Pig Farm in South China. Ph.D. Thesis, South China Agricultural University, Guangzhou, China

McNaughton SJ, Folsom TC, Lee T, *et al.* 1974. Heavy metal tolerance in *Typha latifolia* without the evolution of tolerant races. Ecology, 55: 1163–1165

Qin DH, Zhang KM, and Niu WY. 2002. Chinese Population, Resources, Environment, and Sustainable Development. Beijing: Xinhua Press

Summerfelt ST, Adler PR, Gleen DM, *et al*. 1999. Aquaculture sludge removal and stabilization within created wetlands. Aquacultural Engineering, 19: 81–92

Taylor GJ, and Growder AA. 1984. Copper and nickel tolerance in *Typha latifolia* clones from contaminated and uncontaminated environments. Canadian Journal of Botany, 62: 1304–1308

Truong P, and Hart B. 2001. Vetiver System for Wastewater treatment. Technique Bulletin, No.2001/2, PRVN/ORDPB, Bangkok, Thailand

Wang L, Yang LY, and Wang BZ. 2001. Effective measures for urban wastewater treatment in China. Urban Environment & Urban Ecology, 14(1): 50–52

Xia HP. 2002. Mechanisms and efficiencies on wastewater treatment with constructed wetlands. Chinese Journal of Ecology, 21(4): 52–59

Xia HP, Ao HX, and He DQ. 1994. Effects of environmental factors on vetiver grass growth. Chinese Journal of Ecology, 13(2): 23–26

Xia HP, Liu SZ, and Ao HX. 2002. A study on purification and uptake of garbage leachate by vetiver grass. In: Proceedings of the Second International Conference on Vetiver. Office of the Royal

Xia HP, and Shu WS. 2001. Resistance to and uptake of heavy metals by *Vetiveria zizanioides* and *Paspalum notatum* from lead/zinc mine tailings. Acta Ecologica Sinica, 21: 1121–1129

Ye ZH, Whiting S, Qian JH, *et al*. 2001. Trace element removal from coal pile leachate by an Alabama 10-year old constructed wetland. Journal of Environment Quality, 30: 1710–1719

Ye ZH, Baker AJM, Wong MH, *et al*. 1997. Zinc, lead and cadmium tolerance, uptake and accumulation by *Typha latifolia*. New Phytologist, 136: 469–480

A Brief Introduction to the First Author

Dr. Hanping Xia, a restoration ecologist, is working at the South China Institute of Botany, Chinese Academy of Sciences. Since 1991, he has been engaged in a wide range of R&D on the Vetiver System for the purpose of soil erosion control and polluted environment mitigation, including highway slope stabilization, land reclamation and re-greening, quarry rehabilitation, mine and landfill phytoremediation, wastewater purification, etc. He creatively initiated “the Vetiver Eco-engineering” from his working experience of many years. So far he has one monograph and over 30 academic papers in this aspect published.