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Full Length Research Paper

Potential of a polyculture of *Arundo donax* and *Typha latifolia* for growth and phytotreatment of wastewater pollution

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***Arundo donax* and *Typha latifolia* are emergent macrophyte species that commonly reproduce in humid areas during warm months. This study investigated the growth and pollutant removal capacity of these two species planted in polyculture in a vertical flow filter bed for rural wastewater treatment. Plant shoot height was monitored and biomass production and nutrient uptake were assessed. Water physicochemical parameters were also monitored. *A. donax* showed higher height elongation (288 cm), phytomass production (2.4 kg dry biomass/m²) and nitrogen uptake (21.1 mg/kg DW) than did *T. latifolia*. Phosphorus and potassium retention was identical for both species. The macrophyte bed achieved higher removal rates for biochemical oxygen demand (BOD) (76%), chemical oxygen demand (COD) (82%), total suspended solids (TSS) (96%), total Kjeldahl nitrogen (TKN) (33%) and total phosphorus (TP) (46%), compared to an unplanted basin. The macrophyte species used were able to grow and to contribute to the rural wastewater purification in the adopted experimental constructed wetland.**

Key words: *Arundo donax*, *Typha latifolia*, wastewater, phytotreatment, nutrient uptake, constructed wetland.

INTRODUCTION

Phytoremediation represents the technology of using plants for pollutant removal from the environment. It is a growing field of research in environmental studies because of the advantages of its environmental friendliness, cost effectiveness and the possibility of harvesting the plants for the extraction of absorbed contaminants (Mirza et al., 2010). Among plants, macrophytes are aquatic plants commonly used in constructed wetland (CW) systems for wastewater (WW) treatment (Blake and Dubois, 1982; Brix and Schierup, 1989). Wetlands are considered among the most productive ecosystems in the world (Westlake, 1982) and maximum macrophyte biomass can be favoured by providing nitrogen (Mitsch et al., 1994). Macrophytes assimilate nutrients directly into their tissues, increase environmental diversity in the rootzone and promote a series of chemical and biochemical reactions within biogeochemical cycles (Jenssen et al., 1993). The total amount of nutrients removed by plants and stored in their tissues depends on biomass and nutrient concentration in tissues (Korboulewsky et al., 2012). Moreover, macrophytes translocate oxygen from aerial parts into roots. In this way, the rhizosphere produces an oxygenated micro-environment, encouraging organic matter decomposition and bacterial growth (Gersberg et al., 1986). Conversely, decomposition of macrophytes in wetland may release

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Abbreviations: BOD, Biochemical oxygen demand; **COD,** chemical oxygen demand; **CW,** constructed wetland; **DW,** dry weight; **EC,** electrical conductivity; **S-N-K test,** student-newman-keuls test; **TKN,** total Kjeldahl nitrogen; **TP,** total phosphorus; **TSS,** total suspended solids; **WW,** wastewater.

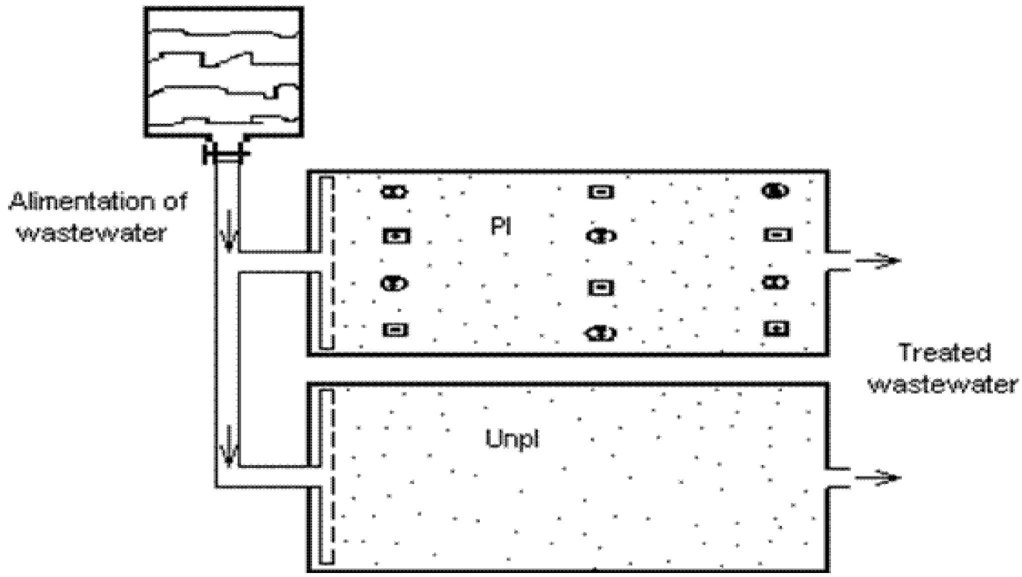

Figure 1. Schematic representation of the experimental constructed wetland system. Pl, Planted basin; Unpl, unplanted basin; ⊡, *Arundo donax*; ⊙, *Typha latifolia*.

large amounts of nutrients (Shilla et al., 2006), and thus could reduce wetland treatment efficiency (Chimney and Pietro, 2006). For this reason, above ground macrophyte biomass harvesting is considered a direct and effective way to solve the re-pollution problem caused by decomposition (Hu et al., 2010), leading to important removal rates of nutrients in short times (Hadad and Maine, 2007) and permitting the control of vegetation spreading (USEPA, 1999). Furthermore, Dubbe et al. (1988) stated that phytomass harvesting enhances macrophyte re-growth during the next growing season.

The use of local plants of economic interest, including macrophytes, in vertical CW systems makes them more exciting because they can be self-financing (Coulibaly et al., 2008). Tanner (1996) defined the general requirements of plant suitability for use in CW systems as: ecological acceptability, tolerance of local climatic conditions, tolerance of pollutants and hypertrophic saturated conditions, rapid establishment and propagation, and high pollutant removal capacity, either through direct assimilation and storage, or indirectly by enhancement of microbial transformations such as nitrification (through root-zone oxygen release) and denitrification (through production of carbon substrates). The selection of plant species with a high capacity for biomass production and/or management practices which induce biomass production would result in greater nutrient removal (Paranychianakis et al., 2006).

Among emergent macrophytes, *Arundo donax* and *Typha latifolia* were widely used in WW treatment in CW (Gersberg et al., 1986; Martin and Fernandez, 1992; Abissy and Mandi, 1998; Ansola et al., 2003; Maddison et al., 2009; Tzanakakis et al., 2009; Mirza et al., 2010; Zhu et al., 2010). *A. donax*, or giant reed, is well known for its adaptability to different ecological conditions, its spontaneous growth capacity and its high biomass productivity (Fiorentino et al., 2010). Recently, Tzanakakis et al. (2009) reported that this species achieved greater shoot- and leaf-potassium and leaf-nitrogen contents than in other plant species. *Typha* spp., or cattail, is a persistent macrophyte that spreads aggressively and has a great reproductive potential and a considerably high nutrient uptake capacity (Maddison et al., 2009). However, limited works exist in the literature on the phytoremediation capacity of *A. donax* (Mirza et al., 2010), particularly when associated with cattails. This study aimed to assess growth, nutrient uptake capacity and contribution to pollutant removal of two local macrophyte species in Tunisia, *A. donax* and *T. latifolia*, used for WW treatment in an experimental vertical flow CW system.

MATERIALS AND METHODS

Experimental set-up

The study was conducted in an experimental plant located at Tunis International Centre for Environmental Technologies (Tunisia). The experimental system consists of two independent rectangular basins (length: 120 cm, width: 90 cm, depth: 40 cm) filled from bottom to top with two gravel layers, the first having a gravel size of 25/40 mm and a thickness of 10 cm, and the second having a gravel size of 3/5 mm and a thickness of 25 cm (Figure 1). Each basin had a 10% slope, and is equipped with a nozzle outlet for discharging the treated WW. The macrophyte species *A. donax* and *T. latifolia* were considered. Young plant shoots of about 20 to 30 cm height were collected from a local ditch and transmitted the same day for plantation. The first bed was planted with a density of 6 shoots/m². The second bed remained unplanted and was considered as a control. Domestic WW was provided from a rural area (Joogar) located 80 km from Tunis, and stored in a container of 1 m^3, installed approximately 0.5 m above the basins. The WW vertical feeding of 30 l/d was performed three times a week. The experiment was carried out during nine months from March to November 2006.

Assessment of macrophyte growth, biomass production and nutrient uptake

Macrophyte growth was monitored monthly by measuring the height of five shoots (two in the input, two in the output and one in the centre of the bed) of each species. Results were presented as monthly averages. The monitoring period lasted about one vegetative cycle, from March to October. In early November, the above ground part (stems, leaves and inflorescence) of all plant stems was harvested. The dry biomass was determined after drying at 70°C to a constant weight. Nitrogen, phosphorus and potassium contents in the biomass of each species were measured as recommended by French standards relating to solid waste (AFNOR, 1999a).

Sampling and analyses

Samples of influent WW and filtrates from the treatment beds were collected monthly. These samples were used to determine the physicochemical characteristics of untreated and treated waters. For this, French Standard Methods for the Examination of water and WW (AFNOR, 1999b) were used to measure pH, electrical conductivity (EC), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), total Kjeldahl nitrogen (TKN) and total phosphorus (TP).

Determination of WW treatment efficiency

Pollutant removal rates (%) were calculated on an influent basis according to the following equation:

Rr (%) = $[1 - (C_f / C_i)] \times 100$

Where, Rr is the removal rate, C_i is the concentration (mg/l) of the considered parameter in the untreated WW (influent), C_f is the concentration (mg/l) of the considered parameter in the treatment bed effluent.

Statistical analyses

The software, Statistical Package for the Social Sciences (SPSS) for Windows (version 10, SPSS Inc., Chicago, IL, USA) was used to determine the statistically significant differences between pollutant concentrations, removal efficiencies and growth parameters applying the Student-Newman-Keuls test (S-N-K test). Pearson correlations between all parameters were also performed. WW samples were taken in triplicate, and results of analyses were presented as mean ± standard deviation.

RESULTS

Macrophyte growth, biomass production and nutrient uptake

The growth of emergent macrophytes was monitored during operation of the CW system through plant height determination and above ground phytomass assessment. Figure 2 presents results of the two parameters. During the growing season, reeds showed a development cycle characterised by a period of rapid exponential growth following a lag phase lasting around 10 weeks, as opposed to cattail shoots whose progress started in March but slowed between April and June. The two plants increased in height to reach maximum values of 288 and 203 cm for *A. donax* and *T. latifolia*, respectively (Figure 2A). Macrophyte cutting was carried out at the end of the vegetative cycle (November). Only the areal parts of both species were harvested. Amounts of the produced aboveground biomass are presented in Figure 2B. The obtained values were about 2.4 kg dry biomass/m² for *A. donax* and 1.5 kg dry biomass/m² for *T. latifolia*. Comparison of biomass obtained for the two macrophytes with S-N-K test showed that reeds produced significantly higher value of dry biomass corresponding approximately to 1.6 times more than for cattails. Furthermore, *A. donax* retained a significantly higher amount of nitrogen (21.1 mg/kg DW) in its aerial parts than did *T. latifolia* (15.1 mg/kg DW) (Figure 2B). However, phosphorus and potassium contents were statistically identical for both species. In contrast to nitrogen and potassium, low phosphorus amounts (< 3 mg/kg DW) were measured in the two plants.

Wastewater treatment performance

Average values of physicochemical characteristics of the raw WW from the rural community of Joogar are summarised in Table 1. The average pH was slightly alkaline (7.98), and conventional pollution parameters were rather elevated. The supplied water was generally characterised by a relatively wide variation of the studied parameters. The efficiency of the macrophyte planted filter in WW treatment was assessed by the quality improvement of analysed parameters. Evolution of physicochemical parameters of both influent and effluents of the treatment beds during the study period are presented in Figures 3, 4, 5. Corresponding removal rates are summarized in Table 3. Figure 3A shows the evolution of pH of the inflow and outflows of planted and unplanted beds during the monitoring period. A significant decrease in pH of the effluents from the two treatment basins has been proven by comparison with that of raw sewage. Mean values decreased from 7.98 in the inflow to 7.12 and 7.13 in outflows of the planted and unplanted beds, respectively. Contrarily to the unplanted bed outflow, the pH of the planted bed outflow followed the pH of the inflow according to a correlation coefficient of about 0.870. Statistical analysis showed that pH values of the two filtrates are significantly different for most of the study period except in March, June, August and November. The pH values of the planted bed diminished during the period of macrophyte active growth (from June to

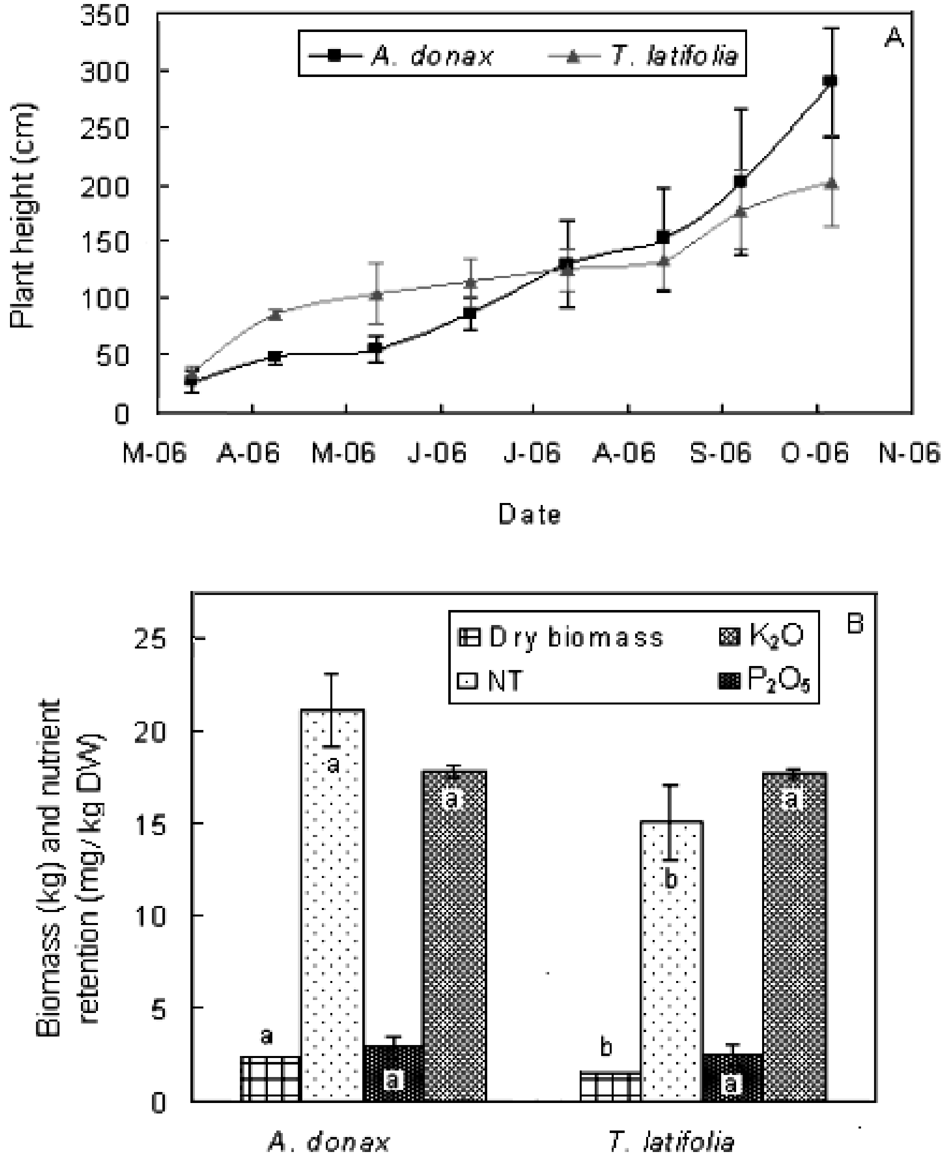

Figure 2. Macrophyte height evolution (A), and aboveground biomass production and nutrient retention (B). *A. donax*, *Arundo donax*; *T. latifolia*, *Typha latifolia*; NT, nitrogen; P_2O_5, phosphorus; K_2O, potassium. Different letters correspond to statistical difference between *A. donax* and *T. latifolia* for each parameter according to the Student-Newman-Keuls test.

Table 1. Physicochemical characteristics of the influent.

Parameter	Units	Mean values ± SD
pH	-	7.98±0.17
EC	mS/cm	2.4±0.7
BOD	mg O_2/l	514±112
COD	mg O_2/l	848±135
TSS	mg/l	822±100
TKN	mg/l	204±31
TP	mg/l	37±8.0

EC, Electrical conductivity; SD, standard deviation; TKN, total Kjeldahl nitrogen; TP, total phosphorus; TSS, total suspended solids.

October). The control basin showed a similar behaviour during the hot season. Evolution patterns of EC of raw and treated WW presented the same shape (Figure 3B). However, there was no significant difference between conductivities of the feed WW and the treatment bed filtrates during all the monitoring period. Also, EC values of treated WW were statistically identical between the sampling dates in each treatment basin. EC values in WW treated by macrophytes ranged between 2.0 and 3.3 mS/cm.

Figure 4A shows the variation of BOD concentrations measured in raw and treated WW during the study period. Loads of inflow BOD decreased during the warm

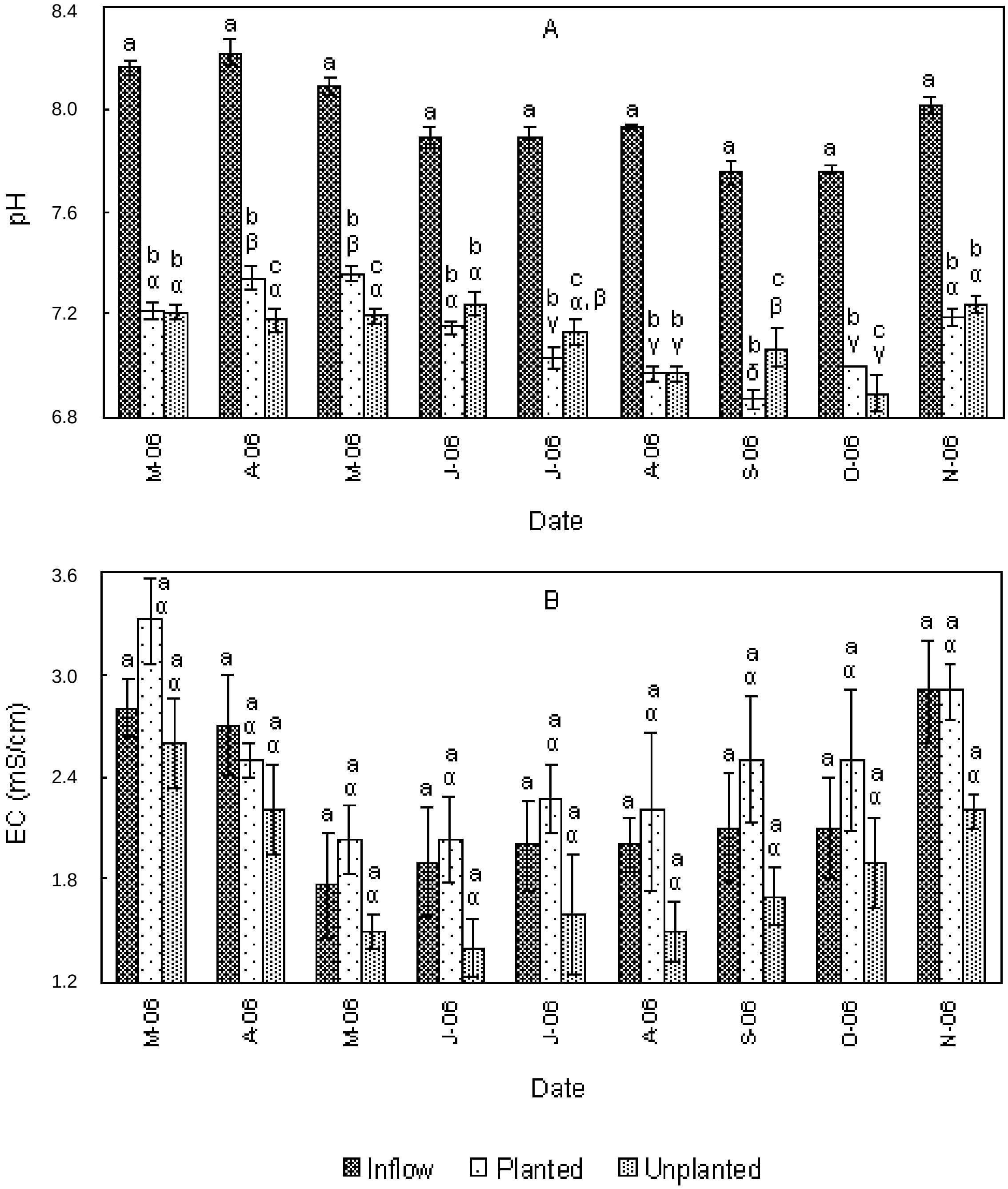

Figure 3. Evolution of pH and electrical conductivity of the influent and effluents of planted and unplanted treatment beds. Planted, outflow of planted basin; unplanted, outflow of unplanted basin. Concentration values are presented as mean of three sampling replicates with standard deviation. Data followed by the same letter are statistically identical between treatments at each date (a, b, c) or between sampling dates for each treatment (α to φ) according to the Student-Newman-Keuls test ($P < 0.05$).

period. At the unplanted basin outflow, the evolution of this parameter partially followed the influent BOD with a correlation coefficient of 0.699 (Table 2), a significant diminution was noted after August. Moreover, BOD values of the control basin, ranging between 110 and 460 mg O_2/l were significantly higher than concentrations of the planted bed. BOD values measured in treated water from the planted bed decreased significantly compared to influent BOD, along the monitoring period. Concentrations ranged between 120 mg O_2/l in March and 270 mg O_2/l in June and only between 30 mg O_2/l in July and 84 mg O_2/l in November. Thus, corresponding removal

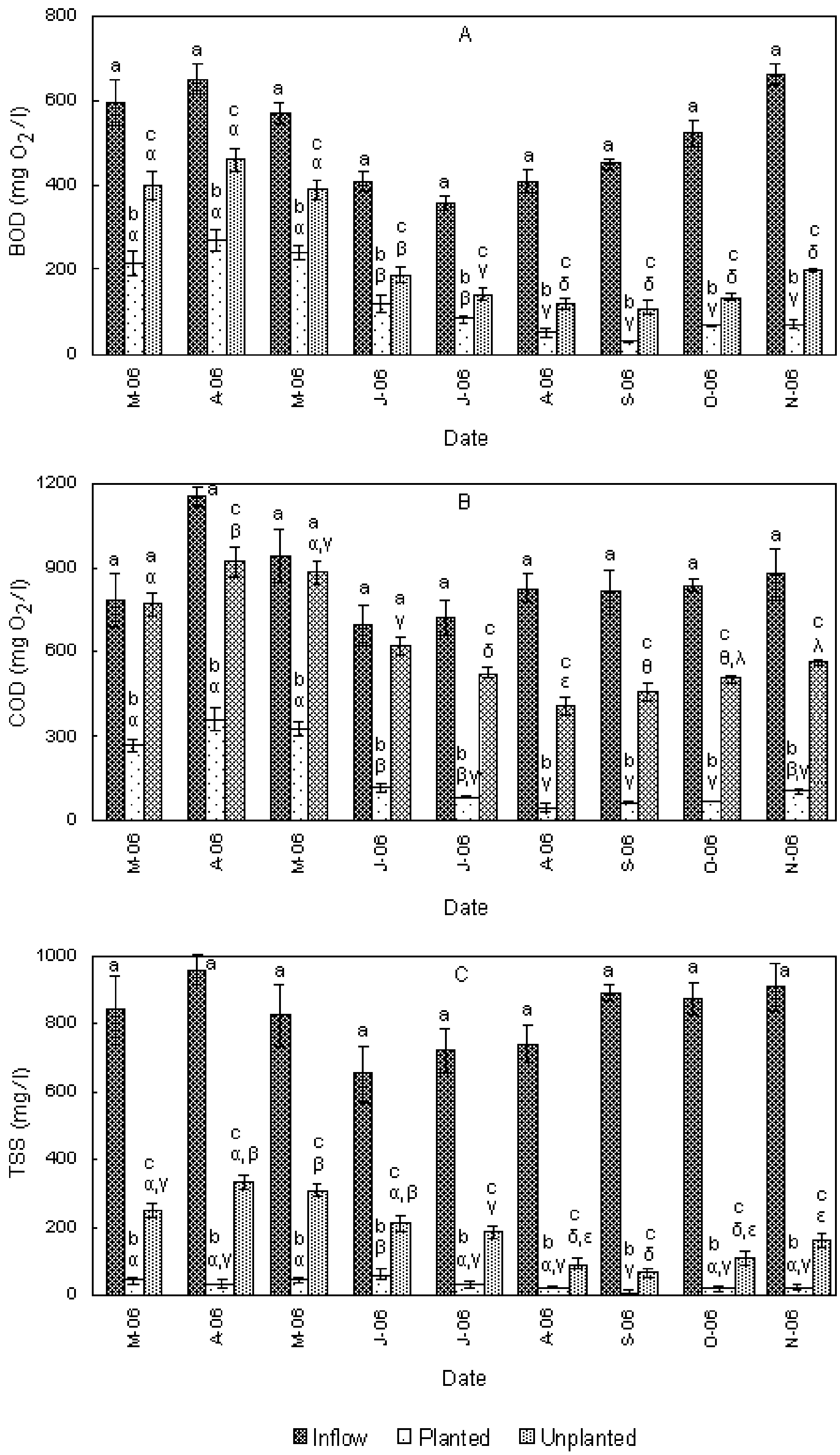

Figure 4. Evolution of organic matter in the influent and effluents of planted and unplanted treatment beds. Planted, Outflow of planted basin; unplanted, outflow of unplanted basin. Concentration values are presented as mean of three sampling replicates with standard deviation. Data followed by the same letter are statistically identical between treatments at each date (a, b, c) or between sampling dates for each treatment (α to φ) according to the Student-Newman-Keuls test ($P < 0.05$).

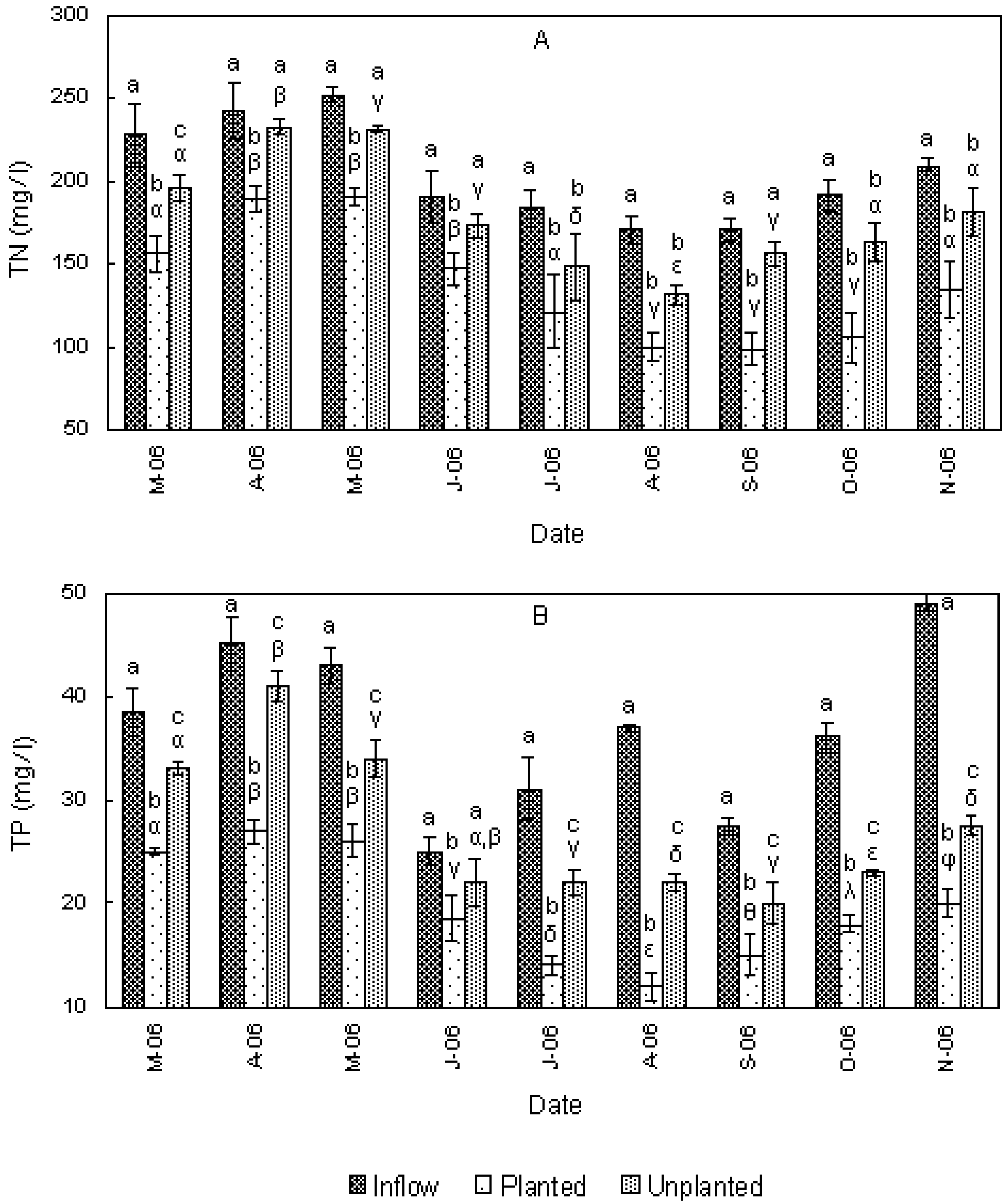

Figure 5. Evolution of nutrients in the influent and effluents of planted and unplanted treatment beds. Planted, Outflow of planted basin; unplanted, outflow of unplanted basin. Concentration values are presented as mean of three sampling replicates with standard deviation. Data followed by the same letter are statistically identical between treatments at each date (a, b, c) or between sampling dates for each treatment (α to φ) according to the Student-Newman-Keuls test ($P < 0.05$).

rates rose importantly between August and November with maximum rate of 93% in September (Table 3).

Concerning the COD, concentrations in the influent varied between 694 and 1150 mg O_2/l (Figure 4B). The planted bed COD decreased significantly with comparison to the inflow and also to the control basin WW.

Table 2. Pearson correlations between pollutants of inflow and outflows of treatment beds.

Parameter		Inflow concentrations				
		BOD	COD	TSS	TKN	TP
Opl	Cc	0.571	0.688*	-0.549	0.638**	0.576
	Rr	-0.338	-0.476	0.701*	-0.692*	0.294
Ounpl	Cc	0.699*	0.634	0.137	0.664**	0.706*
	Rr	-0.467	-0.055	0.151	-0.558	0.192

Cc, Concentrations; Opl, outflow of the planted bed; Ounpl, outflow of the unplanted bed; Rr, removal rates.
*, Significant at the 0.05 level; **, significant at the 0.01 level.

Table 3. Evolution of removal rates of planted and unplanted basins during the monitoring period.

Month	Removal rates (%)									
	BOD		COD		TSS		TKN		TP	
	Pl	Unpl	Pl	Unpl	Pl	Unpl	Pl	Unpl	Pl	Unpl
March	$64±6^{a,α,β}$	$33±3^{b,α}$	$66±4^{a,α}$	$2±0^{b,α}$	$95±3^{a,α,β,γ}$	$70±3^{b,α}$	$31±2^{a,α}$	$14±3^{b,α}$	$35±3^{a,α}$	$14±3^{b,α}$
April	$58±3^{a,α}$	$29±3^{b,α}$	$69±5^{a,α}$	$20±2^{b,β}$	$97±1^{a,β,γ}$	$66±2^{b,β,γ}$	$22±2^{a,β}$	$4±0^{b,β}$	$40±2^{a,α}$	$9±1^{b,β}$
May	$58±4^{a,α}$	$32±3^{b,α}$	$66±3^{a,α}$	$6±2^{b,α,γ}$	$95±1^{a,α,β,γ}$	$62±3^{b,β}$	$25±2^{a,β}$	$8±2^{b,γ}$	$40±2^{a,α}$	$21±1^{b,γ}$
June	$71±4^{a,β,γ}$	$54±3^{b,β}$	$83±3^{a,β}$	$10±3^{b,γ}$	$91±2^{a,α}$	$68±2^{b,α,γ}$	$23±3^{a,β}$	$9±2^{b,γ}$	$26±3^{a,β}$	$12±3^{b,α,β}$
July	$76±4^{a,γ}$	$61±2^{b,β}$	$89±3^{a,β,γ}$	$28±4^{b,δ}$	$96±2^{a,α,β,γ}$	$75±3^{b,δ}$	$34±2^{a,α,γ}$	$19±1^{b,δ}$	$55±3^{a,γ}$	$29±3^{b,δ}$
August	$87±6^{a,δ}$	$71±4^{b,γ}$	$95±3^{a,γ}$	$51±4^{b,ε}$	$97±1^{a,β,γ}$	$88±3^{b,ε}$	$41±2^{a,δ}$	$23±3^{b,δ}$	$68±2^{a,δ}$	$41±2^{b,ε,θ}$
September	$93±2^{a,δ}$	$76±3^{b,δ}$	$92±2^{a,γ}$	$44±3^{b,θ}$	$99±0^{a,γ}$	$93±3^{b,θ}$	$42±1^{a,δ}$	$8±1^{b,γ}$	$45±2^{a,ε}$	$27±3^{b,δ}$
October	$87±2^{a,δ}$	$74±4^{b,δ}$	$92±4^{a,γ}$	$40±2^{b,θ,λ}$	$98±1^{a,β,γ}$	$88±2^{b,ε}$	$45±4^{a,δ}$	$15±2^{b,α}$	$50±3^{a,θ}$	$36±3^{b,ε}$
November	$89±2^{a,δ}$	$70±3^{b,γ}$	$88±3^{a,β,γ}$	$36±3^{b,λ}$	$98±1^{a,β,γ}$	$82±2^{b,λ}$	$36±3^{a,γ}$	$13±1^{b,α}$	$59±2^{a,λ}$	$44±3^{b,θ}$

Pl, Planted bed; Unpl, unplanted bed; TSS, total suspended solids; TKN, total Kjeldahl nitrogen; TP, total phosphorus.
Dates correspond to months of March to November 2006. Data are presented as means of three sampling replicates ± standard deviation.
Data followed by the same letter are not significantly different between columns (a, b, c) and between lines (α, β, γ, δ, ε, θ, λ) for each parameter and for each date according to the Student-Newman-Keuls test.

Reduced concentrations were registered during warm months and lowest values (45 to 81 mg O_2/l) were obtained between July and October. Accordingly, removal rates were significantly enhanced during the same period when percentages exceeded 92% between August and October (Table 3). On the other hand, COD of macrophyte-treated WW was partially correlated (0.688) to the influent values, contrarily to the control effluent (Table 2). At the outlet of the unplanted bed, COD concentrations (405 to 920 mg O_2/l) were statistically identical to the inflow values until July. Minimal COD value, corresponding to the removal rate of 51%, was registered in August. Evolution of TSS concentrations in the influent and filtrates of the treatment basins is shown in Figure 4C. Influent TSS was significantly reduced by treatment in the macrophyte bed filter during all the monitoring period. Indeed, TSS content in the outflow of this basin did not exceed 58 mg/l, and decreased to 6 mg/l in September, unlike the unvegetated bed which had values oscillating between 66 and 330 mg/l. Consequently, removal rates upper to 91% were registered at the outlet of the macrophyte basin in all sampling dates, and reached the highest values of 97 to 99% between August and October (Table 3). However, significantly lower TSS concentrations were recorded in the control bed.

Patterns of influent and effluent TKN are presented in Figure 5A. As with the other parameters, TKN concentrations in the macrophyte bed filter were significantly lower than those of the raw WW along the monitoring period. They importantly decreased during the warm season and stabilized between the months of August and October, minimally reached concentration was of about 98 mg/l. At the outlet of the control basin, TKN content in WW was significantly inferior to the inflow nitrogen amount, but statistically identical to that of the planted bed during the second half of the study period, except in September. Residual concentrations of TKN in treated WW of the two basins were positively correlated to values in the inflow. On the other hand, removal rates corresponding to the planted bed increased during the warm months with maximal percentage of 45% in October, but

Table 4. Pearson correlations between macrophyte growth and pollutant removal.

Parameter	Reed shoot mean height	Cattail shoot mean height
Outflow concentrations		
EC	-0.787*	-0.717*
BOD	-0.799*	-0.763*
COD	-0.758*	-0.704
TSS	-0.741*	-0.687
TKN	-0.811*	-0.707*
TP	-0.647	-0.627
Removal rates		
BOD	0.860**	0.801*
COD	0.819*	0.798*
TSS	0.616	0.546
TKN	0.847**	0.797*
TP	0.500	0.432

EC, Electrical conductivity; TSS, total suspended solids; TKN, total Kjeldahl nitrogen; TP, total phosphorus.
*, Significant at the 0.05 level; **, significant at the 0.01 level.

they varied inversely to the nitrogen feeding content (Table 2). However, these rates were superior to removal efficiencies achieved by the control at all sampling dates. For TP, influent content varied over time but was still consistently higher than that of effluents (Figure 5B). However, concentrations in the outflow of the CW were significantly lower than those of the unvegetated bed at all sampling dates. Low values were registered during the warm months, and minimal residual TP content (12 mg/l) was reached in August. Thus, TP reduction was significantly higher in the filter bed with macrophytes than in the unplanted one.

Relationship between macrophyte growth and pollutant removal

The relationship between macrophyte growth and pollutant removal from WW was investigated by the statistical Pearson test and correlation coefficients are presented in Table 4. The height increase of reed stems was negatively correlated to all pollution indicator concentrations in treated WW. It was positively correlated to removal rates of BOD, COD and TKN, as it was for cattail shoots (Table 4). However, the growth influence of *T. latifolia* on pollutant concentrations in treated water was limited to EC, BOD and TKN.

DISCUSSION

The macrophyte species used in this study have been shown to survive and reproduce well in the treatment filter bed fed with the rural domestic WW. Their growth was rather stagnant during the first months, due partly to the relatively low temperature of below 20°C until May. The active growth was observed during the summer period, with an optimum development between September and October. The warm temperature and solar radiation allowed increase in plant height and density during this period. The reed shoot behaviour was shown to be significantly more important than that of cattails. Moreover, in a recent study, Zhu et al. (2010) observed that *A. donax* was one of the highest biomass productive species if grown in monoculture, and acted by increase of phytomass production in polyculture. Furthermore, Tzanakakis et al. (2009) found that *A. donax* biomass production greatly increased over the course of years, reaching a level of 7.28 kg/m² after three growing cycles. Indeed, this macrophyte species is very efficient in using the sun's energy to produce biomass through photosynthesis (Helder et al., 2010). On the other hand, when compared to *A. donax*, *T. latifolia* produced lower biomass and contained minor levels of nitrogen in its aboveground tissues.

Results of the present study are in accordance with the range of *T. latifolia* biomass (0.3 to 1.8 kg dry biomass/m²) that was obtained by Maddison et al. (2009). Gersberg et al. (1986) also found that the cattail bed was the poorest performer compared to other macrophytes, with regard to pollutant removal from WW. As stated by Boyd (1970), this cattail species could take up and store the key nutrients during the first stages of the vegetative cycle, and translocate them to the meristematic tissues in the period when the ambient conditions for growth are more appropriate. Accordingly, this behaviour would decrease the competition for nutrients with other species during this time. However, these statements contradict the observation of Weiher and Keddy (1995) who reported that *T. latifolia* displace other macrophytes in experimental wetland plant communities. The potential of the polyculture of *A. donax* and *T. latifolia* for WW treatment was investigated by the analysis of treated WW quality and pollutant removal efficiency. One of fundamental factors for water quality is pH that exerts a great influence over the aquatic system. Indeed, this parameter drives many chemical reactions in living organisms. Values registered at the CW outlet point indicate neutral conditions in the treatment system during the monitoring period. Concerning EC, values were similar between raw and plant-treated WW as it was obtained by Coulibaly et al. (2008). Also, the CW effluent was characterized by relatively important EC values. According to Kansiime et al. (2003) and Kanyiginya et al. (2010), high EC in the CW likely indicates an important interaction between WW and macrophytes which improves nutrient uptake.

In another hand, the macrophyte bed filter achieved high BOD and COD removal rates that are consistent with ranges reported in the literature. Indeed, treatment efficiencies by CW combining *T. latifolia* with other macrophyte species were 88 and 76% in Norway (Jenssen et al., 1993), 61 and 60% in Spain (Ansola et al., 2003) and more than 90% in France (Merlin et al., 2002) for BOD and COD, respectively. Recently, Korboulewsky et al. (2012) reported that plants have indirect roles on the water purification through microbial activities, which are importantly engaged in WW treatment, since roots present a great surface area for microbial attachment (Kyambadde et al., 2004). Furthermore, Gersberg et al. (1986) stated that plant translocation of oxygen to an otherwise anaerobic zone within the rhizosphere could stimulate carbonaceous compound biodegradation. Moreover, it was noted that lower pollutant concentrations in treated waters were recorded between July and October, which coincided with the macrophyte active growth phase. This was also the case of TSS exhibiting higher reduction in the considered CW than that reported by Molle et al. (2004) (86%) for purification performance of 54 reed beds in France. Physical mechanisms such as sedimentation and filtration performed at the gravel particles, added to biological filtration of particulate pollutants by plant roots and rhizomes (Gersberg et al., 1986), likely ensure the essentially complete removal of TSS. In a previous study, Brassères and Pietrasanta (1991) found that 30 to 90% of TSS was removed by sedimentation, while only 26 to 36% was eliminated by entrapment in roots in a WW treatment system.

Concerning nutrients, it was clear that corresponding treatment performance was less substantial than removal of the organic matter parameters, which exceeded 75% in the presence of macrophytes. The importance of macrophyte presence and growth for nutrients reduction was also noted in this work. Indeed, the planted bed was significantly more efficient than the unplanted filter for both TKN and TP treatment, in spite of relatively low removal rates. Similarly, Tanner (1996) previously reported that high plant productivity can promote high nutrient removal capacity in CW systems. In such cases, two action modes could be carried out by plants: a direct action through nutrient uptake during the growth phase and an indirect action through microbial processes within the rhizosphere. Exploring nitrogen removal mechanisms, Brassères and Pietrasanta (1991) estimated that TKN removal was 31 to 68% achieved by nitrification and denitrification processes, 2 to 28% by sedimentation, but less than 10% by plant absorption. During bioprocesses, macrophyte roots provide an important surface for the attachment and growth of nitrifying bacteria which use oxygen supplied by roots in order to oxidize ammonia to nitrate (Brassères and Pietrasanta, 1991). After ammonia oxidation, anaerobic denitrifying bacteria reduce nitrogenous products to gaseous nitrogen which escapes to the atmosphere (Ho and Wong, 1994). The role of macrophytes in phosphorus removal is also relatively low, and physicochemical mechanisms such as adsorption, complexation and precipitation are the main processes involved (Tanner et al., 1999). Accordingly, in systems without macrophytes, sediment replaces plants in the role of phosphorus removal (Hadad and Maine, 2007). The increase in residual TP concentration in effluents of the two treatment beds observed at the end of the study period may be due to the active growth of macrophytes when they are present, or to the raw WW quality in the absence of these plants. Indeed, Hadad and Maine (2007) suggested that during the summer, plant growth leads to the accumulation of organic matter in bottom sediments, which in turn decreases the dissolved oxygen and the redox potential of the sediment, releasing phosphorus into the water column.

These results show that plants used in the experimental wetland contributed to reducing pollutants in WW. In return, the CW represented a near optimum environment for macrophyte growth. The rural WW brought sufficient nutrients to support plant growth and to ensure biomass production. Hu et al. (2010) reported that high nutrient concentration in a wetland system accelerates plant growth, and in consequence promotes nutrient removal. Furthermore, high density of emergent plants has the advantage of providing nutrient adsorption and filtration, which is considered as another important factor in nutrient removal (Hu et al., 2010). Other studies have similarly shown that macrophytes having more adventitious roots and larger root surface areas, as it is the case for reeds and cattails, exhibit greater growth levels and achieve higher nutrient removal rates (Kyambadde et al., 2004; Cheng et al., 2009). These root characteristics provide a larger area for attachment and growth of nitrifying bacteria and organic phosphorus de-composing microorganisms, and may also be favourable for inorganic phosphorus absorption, thus enhancing nitrification activities and promoting nitrogen and phosphorus removal (Kymabadde et al., 2004; Lai et al., 2011). Moreover, Hardej and Ozimek (2002) stated that an increase of emergent macrophyte biomass in CW represents an adaptive response in order to raise oxygen translocation to roots, accounting for a more reductive environment in the sediment. On another hand, Martin and Fernandez (1992) suggested that an annual aboveground vegetation harvest carried out after leaf drying could result in removal of 40 to 45% of plant retained N and P, with the rest remaining in rhizomes. These authors proposed an earlier harvest which could be better to prevent autumnal transference of nutrients from shoots to rhizomes. Indeed, a late September to early October harvest would remove about 70% of the nitrogen and phosphorus absorbed by plants through their development cycle.

In the present study, macrophytes harvest was achieved before above ground parts drying, usually occurring in late December, leading to the removal of considerable amounts of absorbed nutrients. Higher nitrogen loads appeared to be removed within *A. donax* aerial tissues. In this investigation, *A. donax* and *T. latifolia* planted in an experimental CW achieved their growth through increase in height and production of phytomass after uptake of nutrients from a rural domestic WW. *A. donax* exhibited greater height elongation and higher biomass production and nitrogen uptake than did *T. latifolia*. The macrophyte filter bed proved significantly higher performance for organic matter and nutrients removal than the control. In conclusion, there was a relative influence of reed and cattail polyculture upon improvement of pollutants removal during WW treatment which would be technically and economically applicable in rural areas in developing countries.

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