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Full Length Research Paper

Domestic wastewater treatment with a vertical completely drained pilot scale constructed wetland planted with *Amaranthus hybridus*

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A pilot scale constructed wetland planted with *Amaranthus hybridus* was developed for domestic wastewater treatment. The reactor system was composed of rectangular beds realized in cement. Each bed was filled from the bottom to the top with 0.1 m of gravel (15/25 mm) and 0.30 m of a white sand originating from the Ebrié lagoon. Two beds planted with yang *A. hybridus* plants (high density: 40 plants/m²; low density: 10 plants/m²) and one control (unplanted bed) were used to perform the experiment. The pH of the overall filtrates decreased from 7 to around 8. Planted beds gave best COD removal (high density = 70%, low density = 66%) than the control (60%). Globally nutrients were best removed in the planted beds (NH_4^+: 69%, PO_4^{3-}: 67%) than in the control (NH_4^+: 15%; PO_4^{3-}: 56%). However the important oxidation of NH_4^+ to NO_2^- and NO_3^- provoked their accumulation in these beds filtrates than in the control. The increase of the plant density seems to have any statistical significant impact upon pollutants removal between the two planted beds experimented. But augmenting plant density allows increasing the beds removal capacities. Plants leaves were less contaminated at 0.5 m height, suggesting it for their harvesting.

Key words: Domestic wastewater, constructed wetland, treatment, ***Amaranthus hybridus***.

INTRODUCTION

Developing countries are nowadays faced with their freshwater quality degradation by wastewater introduction into their environment. The eutrophication of their receiving waters in densely populated areas, causing loss of biodiversity and toxic algae blooms, endangering drinking water supply and limiting recreational activities (Carpenter et al., 1998; Smith et al., 1999; WHO, 2003) is essentially due by the anthropogenic nutrients contained in these wastewaters. It is well known that water pollution may increase water related diseases, which cause human morbidity and death. This situation could maintain for a long time developing countries undeveloped. Receiving water pollution will continue to increase in the next future in these countries because of population concentration in their metrolopolis, lack of budget to provide them with conventional wastewater treatment processes (WHO, 2000).

Consequently, there is a need to develop for these countries adapted technologies for their wastewater treatment. Constructed wetland (CW) seems to be an alternative technology to treat developing countries wastewaters. The CW can easily be integrated in the urban environment, used to treat wastewaters (Billore et al., 1998; Cooper et al., 1996). Moreover, CW is an economical waste treatment system than conventional biological sewage treatment (Kadlec and Knight, 1996). Developing countries dispose of land at low price. Besides, the temperature in these countries is generally favorable to plants, algae and bacteria growths.

The CW concept developed by Seidel (1966) included

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a series of beds composed of sand or gravel supporting emergent aquatic vegetation such as cattails (***Typha***)**,** bulrush (***Scirpus***)**,** and reeds (***Phragmites***)**,** with ***Phragmites*** being the most commonly used. For subsurface wetland, there are some risks of odors, nitrogen gas or nitrous oxide and methane emission to the atmosphere (Mander et al., 2005; Mitsch et al., 2005). The subsurface position of the water, allows plant debris accumulation on the bed surface, offering greater thermal protection. The hydrolysis of that debris contributes to the pollution of the treated water. The surface position of the water above the ground presents risks of mosquitoes development and biomass management problems (Russell, 1999; Thullen et al., 2002; Knight et al., 2003). The utilization of a vertical completely drained constructed wetland planted with edible vegetables, could be suitable for domestic wastewater treatment. Solids containing in the wastewaters could settle on the bed surface and be removed. Irrigation of plants with wastewater may increase their productivities because of water and nutrient resources reused. The removal of nutrients could reduce eutrophication of receiving waters and the attendant risk of toxic algal bloom. Selling of the edible vegetables could contribute to reduce wastewater treatment system exploitation cost. The presence of plants on the beds and its hydraulic option could reduce soil clogging by increasing aeration of the media and avoiding methane emission into the atmosphere.

The aims of this research were (i) to develop a constructed wetland planted with ***Amaranthus hybridus*** (a potential food and feed resource) for domestic wastewater treatment; (ii) to evaluate the performance of the system, (iii) to investigate the impact of plants densities upon the pollutants transformation kinetics, and (iv) to apprehend the biological contamination of the edible vegetable.

MATERIAL AND METHODS

Reactor system

The pilot constructed wetland was composed of 3 rectangular beds (Length x wide x depth = 1.75 x 0.75 x 0.45 m^3) made of cement (Figure 1), giving a bed surface of 1.3 m^2. It was filled from the bottom to the surface by respectively 0.1 m of granitic gravel (15/25 mm), textile and 0.3 m of white lagoon sand. The sand and gravel used were both washed to remove clay, loam and organic materials. Two beds were planted with yang (one month aged) ***A. hybridus*** plants (1 bed at 40 plant/m^2, 1 bed at 10 plants/m^2), and one was preserved unplanted and used as control. The bed bottom slope was 1% oriented towards a PVC pipe (diameter: 0.032 m) for draining the filtrates out of the bed. Each bed was equipped with irrigation devices composed of 8 PVC pipe (length: 1.70 m; diameter; 0.008 m) perforated with 60 lateral holes.

Plant cultivation

The yang ***A. hybridus*** plants (3 weeks aged) were obtained from a previously cultivated ***A. hybridus*** seedbed. The seeds were obtained with the local market gardener. Plants were cultivated on the bed in small holes previously filled with more or less 30 g of local topsoil and they were planted at a distance of 37.5 cm or 26 cm to obtain respectively the high and low density beds.

Water

Two types of water were used in this study: domestic wastewater and potable water. Potable water was used to perform hydraulic essay. Domestic wastewaters obtained from two sewers at Koumassi-Sicogi 1 and Abobo-Sogephia, were stocked in five 1 m^3 feeding tanks (0.7 x 0.7 x 1.10 m) of the pilot system at the University of Abobo-Adjamé, and used to perform the treatment essays. One tank wastewater was used to irrigate only the control bed and the others were applied to the two planted beds. The reactor system was irrigated (0.05 m^3) twice a week (Monday and Thursday), giving an average hydraulic charge of 9.5 x 10^{-3}m/d. Before wastewater application, the feeding tanks were mixed to obtain homogeneous liquor. The water infiltration period was noted and used to calculate the infiltration flow rate into the beds. Wastewater samples were taken into the influent and the filtrate of each cell in an ethylene bottle, preserved at 0°C until analysis.

Plant growth and quality

Plant growth was evaluated by measuring its leaves and stalk characteristics. For each planted bed, five plants (one at each corner (4) and one at the center of the bed) were chosen for the measurement of the leaves and the stalk growth. The mean of these measures constituted the parameter of the plant growth. Leaves growth was evaluated by measuring with a graduated ruler, the length and the maximum width of selected leaves. Stalk growth was evaluated by measurement of its maximum diameter and length with a flexible graduated rubber.

Leaves bacteriological quality

A. hybridus leaves were harvested from the bottom (0.1 m) up to the extremity of its buds (0.5 m) to apprehend their bacterial contamination (Thermotolerant coliform and ***Clostridium perfringens***). For the characterization of the bacteria, 25 g of leaves were weighed and crushed in a crusher (Edmon Buhler) to obtain a solution. Thermotolerant coliform and ***C. perfringens*** were determined according to AFNOR (1994) standard NF T 90-414 and NF T 30-724 methods, respectively.

Physical and chemical parameters

Chemical oxygen demand (COD) and nitrite (NO_2^-) were determined according to USEPA 410.4 and 8 153 methods (EPA, 1979, 1993), respectively. Ammonium (NH_4^+), nitrate (NO_3^-), orthophosphate (PO_4^{3-}), and total hardness were determined according to AFNOR standard NF T 90-015, NF T90-012, NF T 90-023, and NF T90-003 methods, respec-tively. Ca^{2+} and Mg^{2+} were determined according to AFNOR standard NF T 90-005 method. Water electrical conductivity (EC) and salinity were measured with a conductivity meter.

Statistical analysis

The variance analysis was performed using ‘Stastica’ software for comparison of treatment differences (StatSoft, 1997). A significance level of $p < 0.05$ was used throughout the analysis.

Figure 1. Photograph of two vertical completely drained planted beds with ***A. hybridus***.

RESULTS AND DISCUSSION

The mean value of the sand diameters and its uniformity coefficient were respectively 426.66 µm (< 500 µm) and 0.37 (< 2). The sand used was medium grain sand with a uniform distribution. Figure 2 shows the growth of ***A. hybridus*** leaves and stalk. The leaves relatively grew rapidly than the stalk until day 50. During this period, the length and the width of leaves reached respectively 11.63 and 5.12 cm. The length and the diameter of the stalk reached respectively 46.5 and 1.32 cm at the same period. Beyond 50 days, the plant growth increased slowly to become almost constant near 100 days.

This mode of plant growth seems normal, since ***A. hybridus*** has well as others plants growth have two phases; the exponential phase (characterized by fast growth) and the stationary one (characterized by the end of plant growth). Figure 3 shows the evolution of the water infiltration rates into the planted beds and the control. Water infiltration rates in the planted beds were superior to the control one, but decreased on the overall beds with time. On days 35, 40 and 46, the solids accumulated on the different beds surfaces were removed and these beds were plough on the first 10 cm. The consequence of this treatment was the increase of the water infiltration in the beds. The reduction of the water infiltration rates in the beds could be explained by solids settlement and biofilm development (Wu and Huang, 2000). The superiority of the water infiltration into the planted beds to the control could be explained by the channels developed by the plants roots in the bed. These channels improve planted beds permeabilities, contributing in this way to water infiltration increase in these beds than in the control.

Despite the positive impacts of plants upon the hydraulic conductivity of the bed media, the planted beds were clogged. This result could be explained by the saturation of the channels developed by the plant roots and the small pores of the bed (Sanford et al., 1995). The statistical analysis had given a significant difference ($p < 0.05$) between water infiltration rates on the planted beds and the control. This result could be explained by amelioration of the beds permeabilities by plant roots. The comparison between the water infiltration rates of the planted beds with ***A. hybridus*** at different densities, had given no significant difference ($p > 0,05$). This result could be explained by the two densities used. May be these densities do not allow obtaining significant difference between the plant roots densities that impact significantly the beds permeabilities.

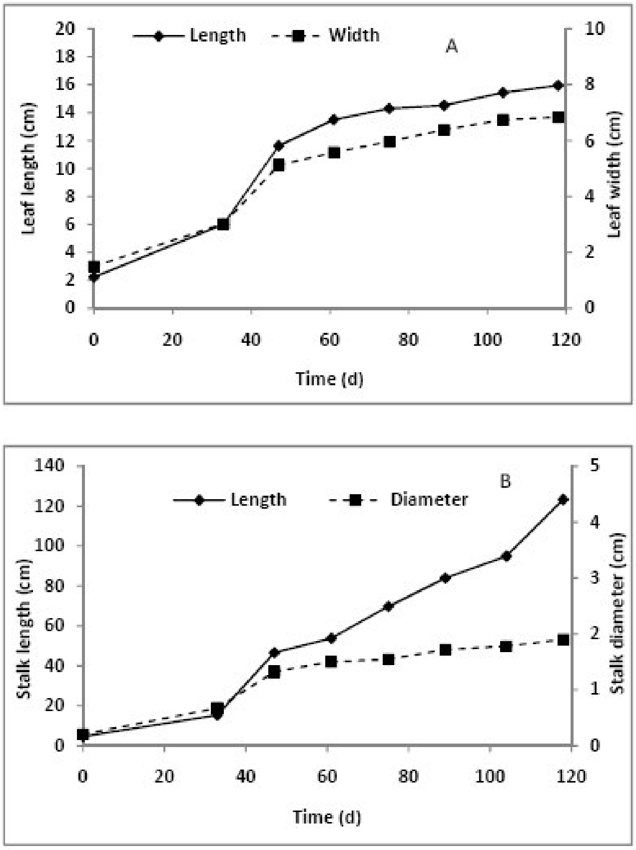

Figure 2. Kinetics of ***A. hybridus*** leaves and stalk growth on the constructed vertical completely drained beds. A: leaf growth; B: stalk growth.

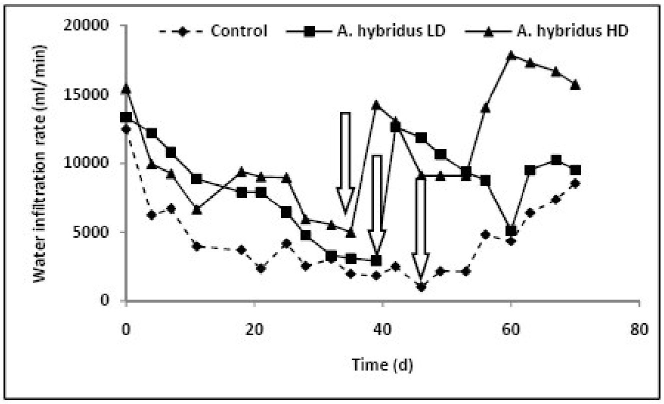

Figure 3. Water infiltration rates profiles in the control and planted beds with ***A. hybridus*** at low (LD) and high (HD) densities. The arrows indicate the period of solids removal on the bed surface

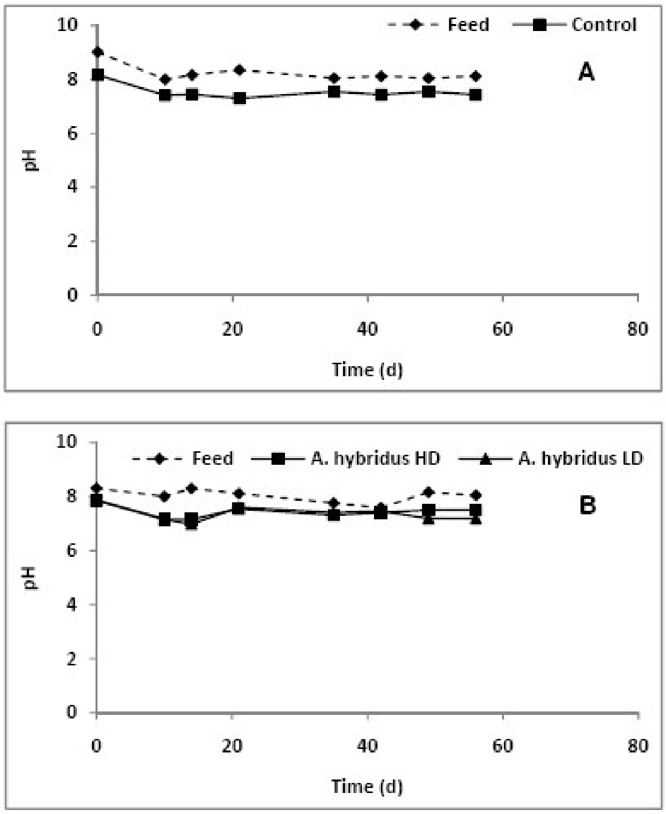

Figure 4. pH profiles in the raw wastewater and in the filtrates of the control (**A**) and the planted beds (**B**) with ***A. hybridus*** at low (LD) and high (HD) densities.

Figure 4 shows pH evolution in the raw wastewater and the beds filtrates. The sequence of the pH mean values after the experimental period was: raw wastewater (8) > filtrate of control (7.47) > filtrate of planted bed with ***A. hybridus*** at low density (7.43) > filtrate of planted bed with ***A. hybridus*** at high density (7.41). This result is different from that obtained by Finlayson and Chick (1983). These authors had obtained an increase of the pH into the filtrates of their planted beds with ***Typha latifolia***. The difference between the result of these authors and this study could be explained by the impact of nitrification on the planted beds filtrates acidity. It is well known that nitrification of 1 g of NH_4^+ requires about 7.07 g of alkalinity as $CaCO_3$ (Tchobanoglous et al., 2003). Nitrification is influenced in a planted wetland by the oxygen concentration of the media, which is bringing in subsurface flow wetland by the plant roots and by oxygen transfer at the interface atmosphere-bed surface. Indirectly, the plant types used could influence oxygen transfer in the sand media, which can more or less impact nitrification. So, nitrification will be induced by a plant transferring high concentration of oxygen in its roots zones, with regard to plant transferring low oxygen in the same media. As a consequence, more alkalinity will be consumed (pH decrease) in the media with high oxygen than a media with low oxygen.

Figure 5 shows NH_4^+ evolution in the raw wastewater, the filtrates of the planted beds and the control. The mean value of NH_4^+ removal by the control, planted bed with ***A. hybridus*** at low density and planted bed with ***A.***

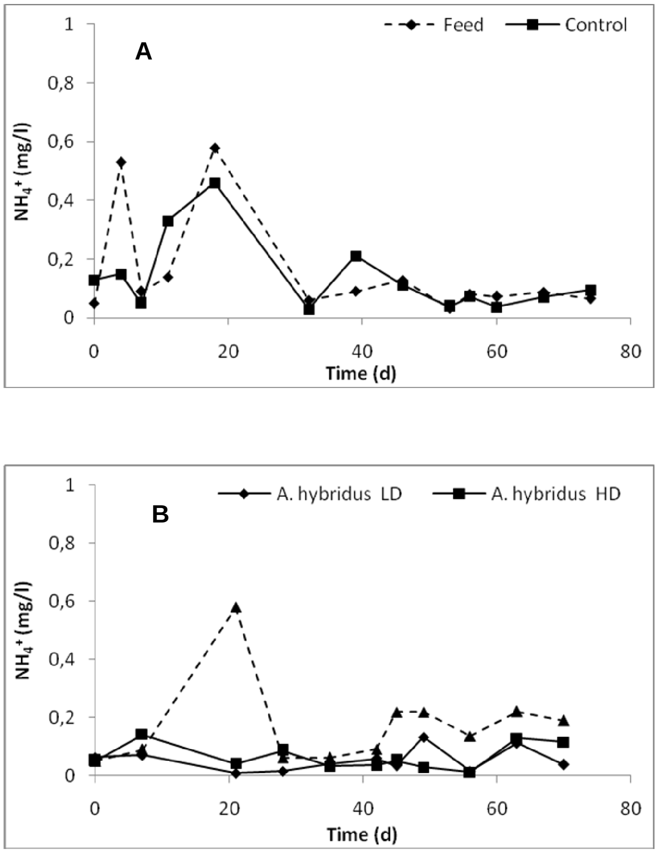

Figure 5. Kinetics of NH_4^+ removal in the control (**A**) and the planted beds (**B**) with ***A. hybridus*** at low (LD) and high (HD) densities.

hybridus at high density were respectively about 15, 62 and 69%. But NH_4^+ removal varied between 22 – 88% and 38 – 92% for the planted beds with ***A. hybridus*** at low and high densities, respectively. The results of this study are similar to those of Abissy and Mandi (1998). These authors had observed a better reduction of NH_4^+ in their planted bed than in the control (unplanted bed). Statistical analysis of the two planted beds did not show a significant difference ($p > 0.05$) between the concentrations of NH_4^+ in their filtrates. But there was an interest to augment the plant density, since this increased NH_4^+ removal.

Figure 6 shows the evolution of NO_2^- in the filtrates of the control, the planted beds with ***A. hybridus*** as well as in the raw wastewater. There was an increase of nitrite concentration in the control and the planted bed with ***A. hybridus*** at low density than in the raw wastewater and the planted bed with ***A. hybridus*** at high density. The mean value of nitrite over the experimental period in the raw wastewater, the filtrates of the control, planted bed with ***A. hybridus*** at low density and at high density were respectively 1.6, 4.7, 10.4 and 1.3. The increase of nitrite concentration in the filtrates of the control and the planted bed with ***A. hybridus*** at low density suggest a nitrification

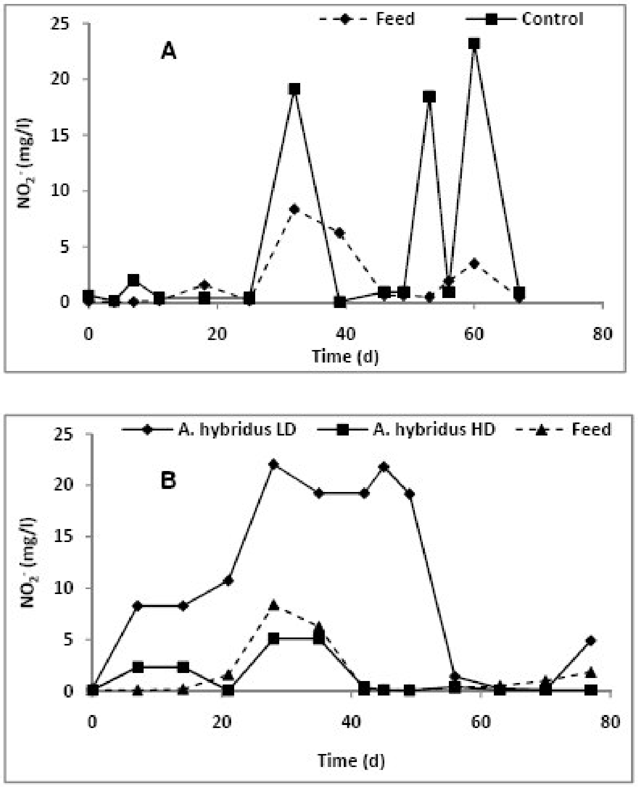

Figure 6. NO_2^- profiles in raw wastewater, filtrates of control (**A**) and the planted beds (**B**) with ***A. hybridus*** at low (LD) and high (HD) densities.

in these beds. Nitrite accumulation in the filtrates could result from a combine action of an important nitritation of NH_4^+ and low nitratation of the total NO_2^- to NO_3^-, because of the short hydraulic retention time (Sirianuntapiboon et al., 2006). But the decrease of NO_2^- concentration in the planted bed with ***A. hybridus*** at high density filtrate could attest a best nitratation process than in the others beds.

Figure 7 shows NO_3^- profiles in the beds filtrates and in the raw wastewater. Nitrate concentrations in the beds filtrates were superior to its concentrations in the raw wastewater (mean value 36 mg/l). Comparing the concentration of NO_3^- in the beds filtrates allows distinguishing in the following order: planted bed with ***A. hybridus*** at high density (mean value: 86 mg/l) >; planted bed with ***A. hybridus*** at low density (mean value:78 mg/l) >; control (mean value: 54 mg/l).

The important accumulation of NO_3^- concentration in the planted beds filtrates gives evidence that the nitrification was induced in these beds than in the control. NH_4^+ removal mechanisms in wetlands are usually of physical, chemical or biological orders (Tanner, 1996; Xue et al**.,** 1999; Vymazal, 2002; Toet et al., 2005; Nurk et al**.,** 2005). However, the high concentrations of NO_2^- and NO_3^- in the planted beds filtrates suggest that the biological activity was the dominant process. In the plant-

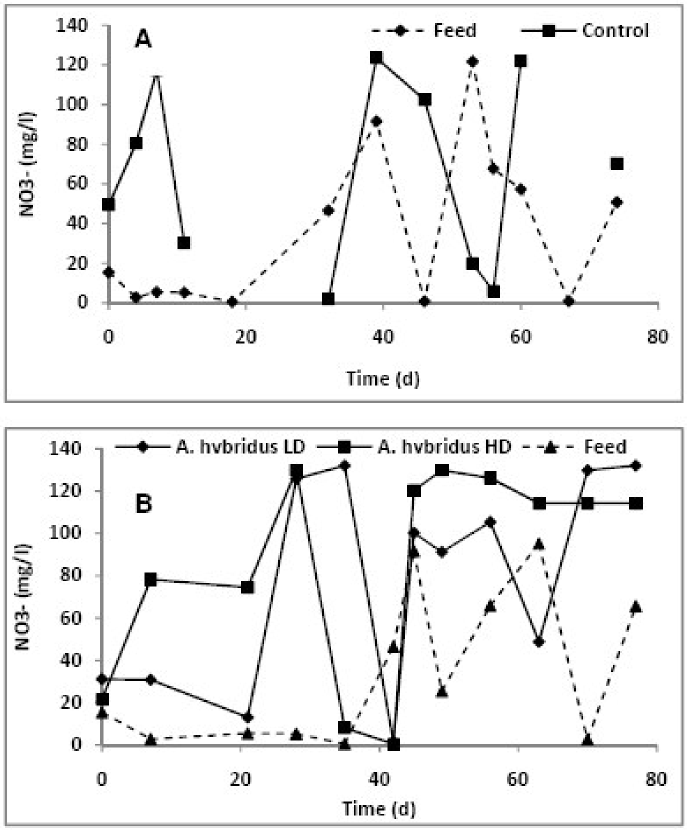

Figure 7. Profiles of NO_3^- in raw wastewater (feed), filtrates of control (**A**) and the planted beds (**B**) with ***A. hybridus*** at low and high densities.

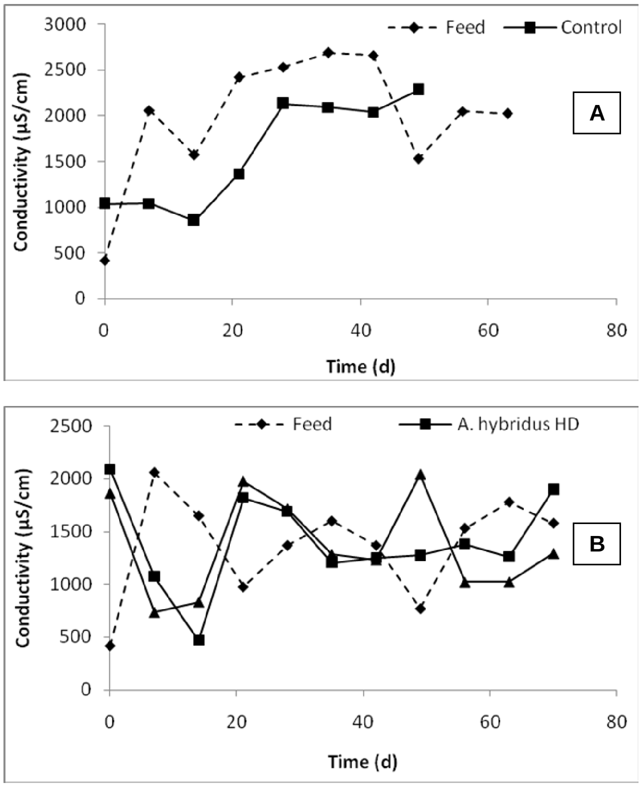

Figure 8. Electrical conductivity (EC) profiles in raw wastewater, the filtrates of the control (**A**) and the planted beds (**B**) with ***A. hybridus*** at low (LD) and high (HD) densities.

ed beds, via photosynthesis, oxygen is abundantly transferred in the roots zones and that optimized nitrification bacteria activities (Gesberg et al., 1986; Armstrong and Armstrong, 1988 1990). As a consequence, NO_3^- is more accumulated in the filtrates of the planted bed which receives more oxygen (planted bed with ***A. hybridus*** at high density) than the others (planted bed with ***A. hybridus*** at low density, control). The transparencies of the beds filtrates were highly improved than the raw wastewater. But the quality of the control filtrate was best ameliorated than the planted beds. This result could be explained by the important settlement of solids and colloids in the control bed media. In the planted beds, plant roots create some channels through which solids migrate to the filtrate, degrading its transparency. Figure 8AB shows the electrical conductivity (EC) profiles in the planted beds and the control filtrates as well as in raw wastewater. EC varied randomly and there was no significant difference between the planted beds filtrates and the raw wastewater conductivities. There was also any plant density influence upon the EC of the planted beds filtrates. A similar result was obtained by Riviera et al. (1996) on the filtrate of their wetlands. On contrary Abissy and Mandi (1998) had obtained in their planted bed filtrate an EC superior to that of the control, which was established in uncovered soil.

The difference between the results of these authors and this study could be explained by the quality of the soil used. Abissy and Mandi (1998) had used a soil rich in organic matters, on contrary the sand of this study lacks these materials. The oxidation of organic matters may create acidic condition because of CO_2 release; as a consequence, salts lixiviate from the bed media, and increase the filtrates EC. Figure 9 shows the total hardness profiles in the planted beds as well as the control filtrates. The total hardness of the raw wastewater (mean value: 173 mg/l) was inferior to the beds filtrates (mean value: 218 - 294 mg/l) ones. The total hardness increased in the filtrates were 122, 126 and 170% respectively for the control, planted beds with ***A. hybridus*** at high and low densities.

There was no significant difference ($p > 0,05$) between the total hardness of the filtrates of the planted beds, the control and the raw wastewater. The increase of the total hardness of the various beds filtrates than the raw wastewater could be explained by a release of Ca^{2+} and or Mg^{2+} in these filtrates. This release could result from an ion exchange between Na^+ or K^+ containing in the raw wastewater and Ca^{2+} or Mg^{2+}, dissolution or washing of rocks containing Ca^{2+} or Mg^{2+} in the sand media (Jackson and Myers, 2002). The profiles of Ca^{2+} or Mg^{2+} in the

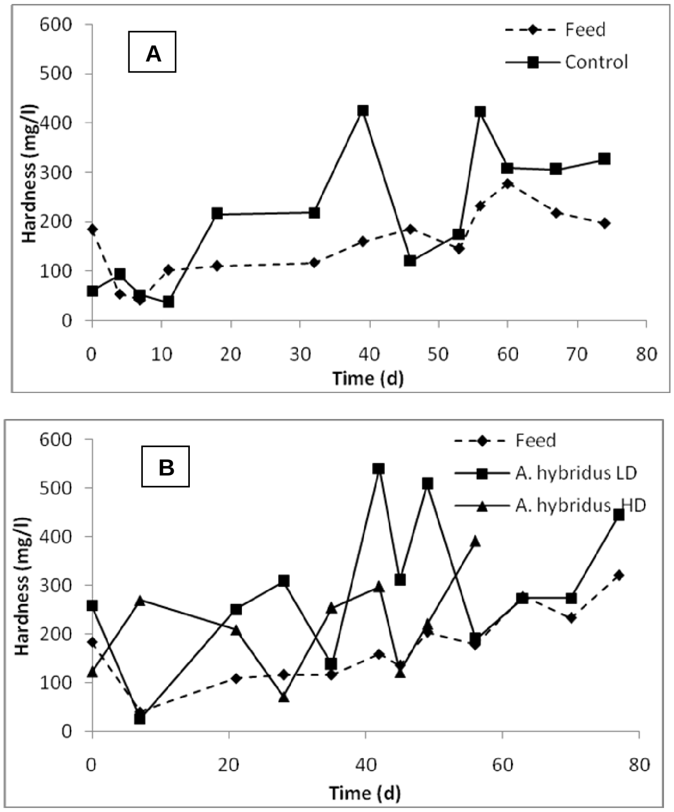

Figure 9. Total hardness profiles in raw wastewater (feed), the filtrates of the control (A) and the planted beds (B) with ***A. hybridus*** at low (LD) and high (HD) densities.

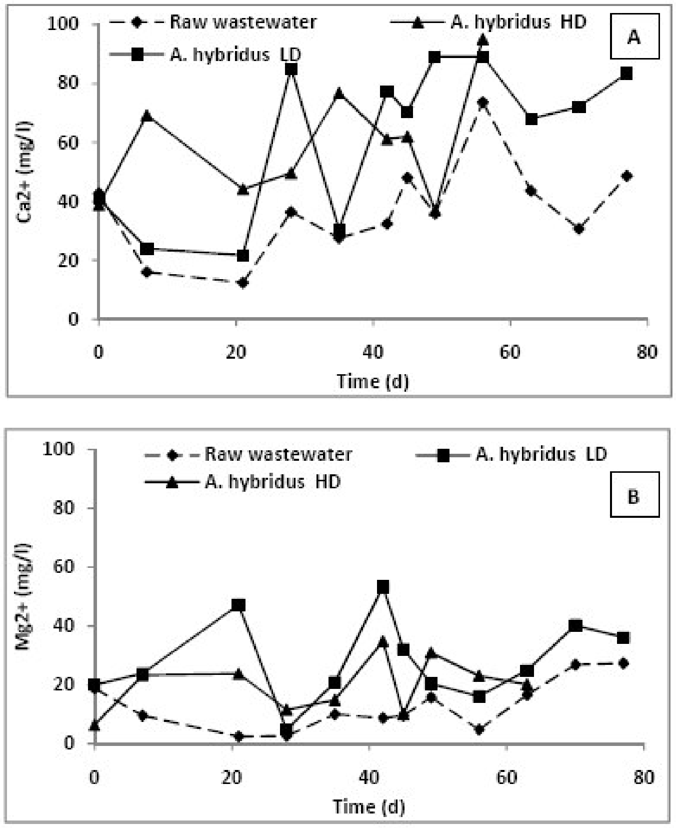

Figure 10. Profiles of Ca^{2+} (**A**) and Mg^{2+} (**B**) in the raw wastewater (feed), the filtrates of the planted beds with ***A. hybridus*** at low (LD) and high (HD) densities.

various beds filtrates show an increase of their concentrations than in the raw wastewater, confirming their release into the filtrates (Figure 10).

Figure 11 shows the profiles of COD in the filtrates of the planted beds, the control as well as in the raw wastewater. COD removals varied in the filtrates of the planted bed with ***A. hybridus*** at low (13 - 94 %) and high (24 - 96%) densities, and the control (14 - 90%). But COD removals mean values over the experimental period were 60, 66 and 70% respectively for the control, the planted bed with ***A. hybridus*** at low and high densities. Comparing COD concentrations of the various beds filtrates with that of the raw wastewater gave a significant difference ($p < 0.05$). However, there was no significant difference ($p > 0.05$) between the COD of the planted beds filtrates and the control one. The same result was obtained when comparing the COD in the filtrates of the two plants densities tested. Although the difference was not significant when plant density was varied from 10 to 40 plants/m^2 on the beds, there was an interest, because of COD removal enhancement from 66 to 70%. The enhancement of COD removal parallel to the plant density increase could be explained by the optimization of microbial oxidation activities of organic pollutants in the planted beds (Brix, 1994). The removals of COD by the planted beds in this study are superior to that obtained by Urbanc-Beric (1994) (36%). The differences observed between the two researches, could be explained by the plant type used, the nature of the beds, and the hydraulic retention time of the reactors (Sirianuntapiboon et al., 2006).

Figure 12 shows PO_4^{3-} profiles in the filtrates of the various beds and in the raw wastewater. PO_4^{3-} concentrations in the filtrates of the beds were lower than in the raw wastewater, traducing its removal in the beds. The mean values of orthophosphate removal after 80 days in the control, planted bed with ***A. hybridus*** at high and low densities were respectively 56, 49 and 67%. Above 80 days, the removal of orthophosphate by the control dropped to 46% and that of planted bed with ***A. hybridus*** at high density increase to 65% (result not presented here).

These results suggest that the mechanisms of PO_4^{3-} removal in the reactor system are the combining actions of physical or chemical reactions and biological uptake as proposed by Kadlec and Knight (1996). The increase of the plants density had no significant effect upon orthophosphate removal. This result is evidence, because although phosphorus uptakes by plant are dependent on plant type, it is generally small (Hocking, 1989; Cooke,

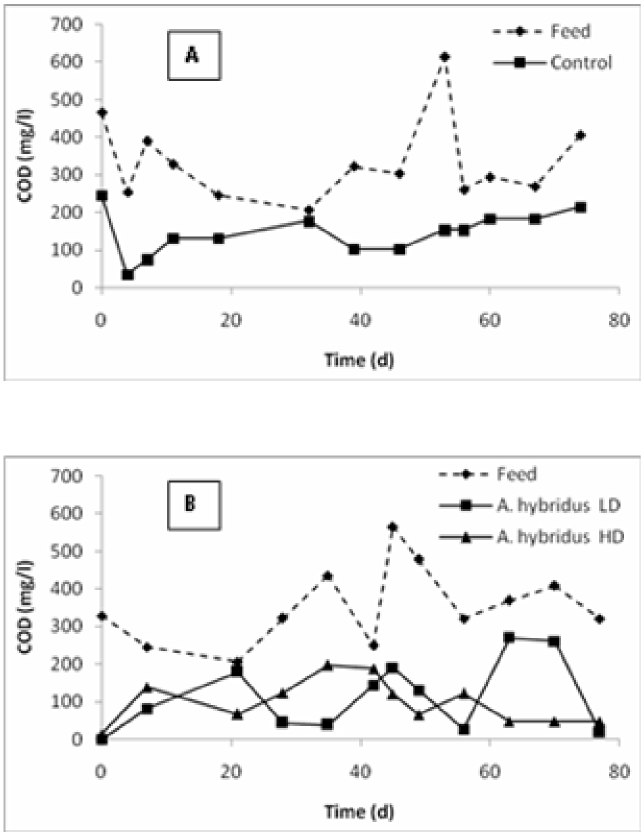

Figure 11. COD removal profiles in raw wastewater (feed), the filtrates of the control (**A**) and the planted beds (B) with ***A. hybridus*** at low (LD) and high (HD) densities.

1992; Ansola et al., 1995). But there is an interest to cultivate ***A. hybridus*** on the bed, since PO_4^{3-} removal increased than the control. The dominant process in PO_4^{3-} removal in this study could be of chemical or physical orders (precipitation of PO_4^{3-} by Ca^{2+}, adsorption) in the sand media and its retention in the beds. The experimental condition (pH ≥ 7, high concentration of PO_4^{3-} and Ca^{2+}) is favorable to such reaction (Nichols, 1983; Howard-Williams, 1985).

About the bacterial contamination of the vegetable produced, bacterial concentration on plant leaves falls with the plant height. Bacterial population of the leaves was reduced about 50% at 50 cm from the surface of the planted bed comparing with its concentration at 10 cm (Figure 13). This result attests that the irrigation devices used do note contaminate the plant leaves and suggests 50 cm to be the height at which those can be harvested with low risk.

Conclusion

The wetland developed has proven goods capacities for removing COD, NH_4^+ and PO_4^{3-} from domestic wastewater. COD was best removed in the planted beds than

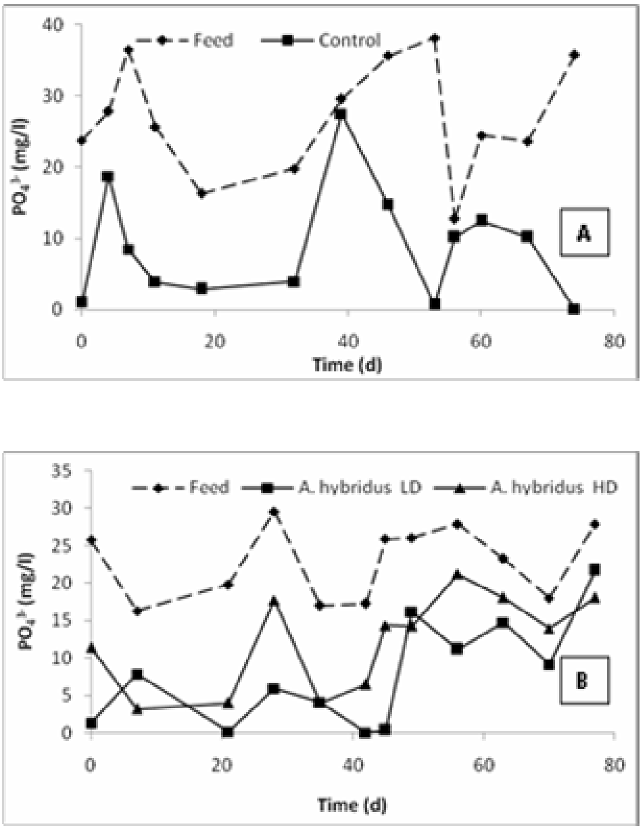

Figure 12. PO_4^{3-} removal profiles in raw wastewater (feed) and the filtrates of the control (A) and the planted beds (B) with ***A. hybridus*** at low (LD) and high (HD) densities.

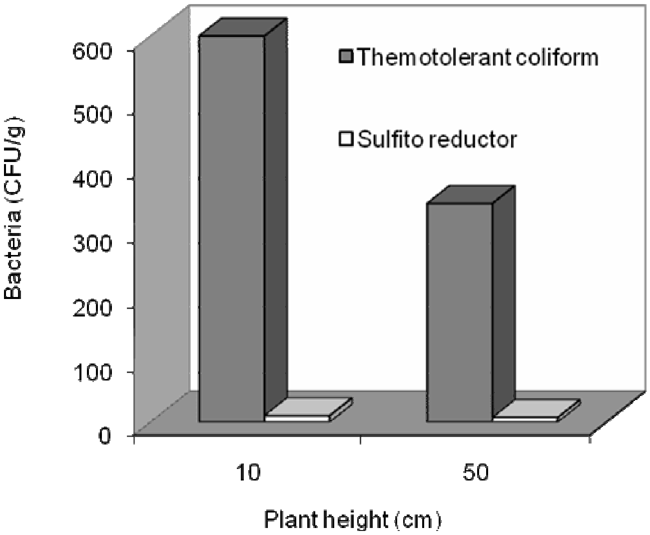

Figure 13. ***A. hybridus*** leaves contamination profiles by Thermotolerant coliform and Sulfito reductor bacteria.

in the control. Ammonium was oxidized to NO_2^- and NO_3^-. Orthophosphate was removed in the planted beds with ***A. hybridus*** at low density (67%) than in the control (56%).

The presence of plants improved globally pollutants degradation and increased water infiltration into the beds. The pH of the planted beds filtrates (7 ≤ pH ≤7.43) decreased than the raw wastewater (pH = 8.15). The leaves of the vegetables produced were less contaminated at 0.5 m from the surface of the beds, suggesting this height for their harvesting.

In conclusion, there was a relative influence of plant density upon some pollutants removals and beds clogging reduction. Although, the positive effect between the planted beds was not statistically significant.

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