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Treatment of Hydroponics Wastewater Using Constructed Wetlands in Winter Conditions

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Abstract Hydroponics culture generates large amounts of wastewater that are highly concentrated in nitrate and phosphorus but contains almost no organic carbon. Constructed wetlands (CWs) have been proposed to treat this type of effluent, but little is known about the performance of these systems in treating hydroponic wastewater. In addition, obtaining satisfactory winter performances from CWs operated in cold climates remains a challenge, as biological pathways are often slowed down or inhibited. The main objective of this study was to assess the effect of plant species (*Typha* sp., *Phragmites australis*, and *Phalaris arundinacea*) and the addition of organic carbon on nutrient removal in winter. The experimental setup consisted of 16 subsurface flow CW mesocosms (1 m^2, HRT of 3 days) fed with 30 $L d^1$ of synthetic hydroponics wastewater, with half of the mesocosms fed with an additional source of organic carbon (sucrose). Carbon addition had a significant impact on nitrate and phosphate removal, with removal means of 4.9 g $m^{-2} d^{-1}$ of NO_3-N and 0.5 g m^{-2} d^{-1} of PO_4-P. Planted mesocosms were generally more efficient than unplanted controls. Furthermore, we found significant differences among plant treatments for NO_3-N (highest removal with *P. arundinacea*) and COD (highest removal with *P. australis*/*Typha* sp.). Overall, planted wetlands with added organic carbon represent the best combination to treat hydroponics wastewater during the winter.

Keywords Constructed wetlands · Hydroponics wastewater · Macrophyte species · Nitrate removal · Organic carbon addition

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1 Introduction

Hydroponics culture requires large quantities of water and chemical fertilizers to optimize plant production. Consequently, this type of agriculture produces large amounts of point source pollution highly concentrated in nitrate (200–300 mg NO_3-N L^{-1}) and phosphorus (30–100 mg PO_4-P L^{-1}), but containing almost no organic carbon (Park et al. 2008; Prystay and Lo 2001). Current technologies for hydroponics wastewater treatment—ultrafiltration, reverse osmosis—are efficient (Koide and Satta 2004) but have high operational and maintenance costs compared with extensive wastewater treatment systems. Constructed wetlands (CWs), especially horizontal subsurface flow constructed wetlands (HSSF CWs), have been proposed as an efficient and inexpensive alternative to treat hydroponics wastewater (Grasselly et al. 2005).

The complex and positive contribution of macrophytes to overall pollutant removal in HSSF CWs is currently widely accepted (Brix 1997). For instance, plants may supply organic carbon to stimulate denitrification (Zhu and Sikora 1995) when wastewaters are rich in nitrate but poor in organic carbon (e.g., hydroponics wastewater). However, carbon compounds from root exudates could be insufficient to completely remove high concentrations of nitrate. Indeed, Prystay and Lo (2001) reported low nitrate removal (13–27%) that was comparable to unplanted systems in HSSF CWs planted with *Typha latifolia* and treating hydroponics wastewater. Also, as production of root exudates and denitrification capacity differs among plant species (Lin et al. 2002), other macrophyte species could yield different results. Hence, determining which species are more efficient under a variety of conditions remains necessary (Brisson and Chazarenc 2009).

In addition to the organic carbon supplied by plants, an external source of organic carbon may be required to obtain satisfactory nitrate removal when wastewater nitrate concentrations are high (Lin et al. 2002; Zhu and Sikora 1995). Methanol, ethanol, acetic acid, glucose, fructose, and starch are common external carbon sources used to enhance denitrification in carbon-poor effluents (Her and Huang 1995; Huett et al. 2005; Park et al. 2008). However, complete denitrification requires a specific ratio of carbon/nitrogen that varies depending on carbon type and lability (Her and Huang 1995). Optimal nitrate removal in constructed wetlands was observed at a chemical oxygen demand (COD)/N ratio of 3.5 using fructose as a carbon source (Lin et al. 2002) and a C/N ratio of 3 when methanol was used (Huett et al. 2005). However, plant species, effluent type, and loading could interact with the effects of carbon addition, resulting in different ratios than those previously reported.

CWs operated in cold climates face another challenge, as winter removal efficiency must remain satisfactory with reduced rates of biological removal pathways and plant dormancy (Kadlec and Wallace 2008). Although denitrification rates decline with colder temperatures, nitrate removal in HSSF CWs was observed at temperatures as low as 4°C (Sirivedhin and Gray 2006). Also, significant differences observed among plant species during summer may become non-significant during winter (Riley et al. 2005). This highlights the need to better quantify the effects of winter on nutrient removal and potential interactions with other factors (e.g., effects of plants).

We used a mesocosm experiment to assess the individual and combined effects of plant species (*Typha* sp., *Phragmites australis*, and *Phalaris arundinacea*), and the addition of organic carbon (sucrose) on nutrient removal from hydroponics wastewater in HSSF CWs operated in winter conditions. Given the constraints of winter operation and composition of hydroponics wastewater, its optimal year-round treatment with HSSF CWs represents a real challenge, and suitable operating conditions can only be identified with the simultaneous evaluation of several factors as we report in this study.

2 Material and Methods

2.1 Experimental Setup

The mesocosm experiment ran from November 2007 to April 2008 in a controlled greenhouse located at the Botanical Garden of Montreal. The experiment simulates a HSSF CW under a temperate climate with cold winters (no plant activity). In this case, the belowground environment of constructed wetlands does not freeze due to soil insulation, flowing wastewater, and often insulation by snow cover. Air temperature in the greenhouse (and thus, mesocosm temperature) was kept at a minimum of 5°C (average 8°C). To further simulate winter conditions, at the beginning of the experiment, the aboveground portion of the macrophytes (most of which was already in senescence) was harvested and removed. The greenhouse was also shaded with a large tarp to reduce light and temperature as an additional measure to prevent any aboveground plant activity.

The experimental setup consisted of 16 subsurface flow mesocosms of 1 m^2 (1.25 m long, 0.8 m wide, and 0.3 m deep) operated at a HRT of 3 days. The mesocosms were filled with granitic river gravel (Ø= 10–15 mm), with a narrow section at the inlet filled with granitic coarse gravel (Ø=30–40 mm) to facilitate water distribution. Water level was kept 4 cm under the substrate surface. The mesocosms were planted in monocultures of *Typha* sp., *P. australis*, and *P. arundinacea*, in addition to unplanted controls with four mesocosms for each of the four species treatments. The treated effluent was collected daily at the outlet of each mesocosm. The mesocosms were planted in 2002 from rhizomes and were used to treat fish farm wastewater until 2006 (Ouellet-Plamondon et al. 2006). In the summer of 2007, the mesocosms were fed with reconstituted hydroponics wastewater for acclimatization before the first experimental measurements were conducted in November 2007.

2.2 Wastewater Characteristics

Two types of wastewater were used, one with reconstituted hydroponics wastewater only and the other with the same hydroponics wastewater but supplemented with organic carbon (sucrose). The hydroponics wastewater was reconstituted using chemical fertilizers following effluent nutrient concentrations published by Prystay and Lo (2001), Park et al. (2008), Koide and Satta (2004), as well as information collected by personal communication with greenhouse producers (see Table 1 for concentrations and loading). The wastewater with organic carbon had the same fertilizer concentration but was supplemented with sucrose to reach a final concentration of 815 mg COD L^{-1} (C/N, 1.3; COD/N, 3.5). During the experiment, half of the mesocosms received chemical fertilizers only while the other half received fertilizers supplemented with organic carbon. This resulted in two mesocosms being attributed to each of the eight combinations of species/wastewater treatments. The mesocosms received wastewater in an intermittent batch mode of 30 $Lm^{-2}d^{-1}$. New wastewater solutions were prepared approximately every week and stored in refrigerated bulk tanks (4°C) until delivery to prevent major changes in wastewater composition.

2.3 Physical–Chemical Analyses

Inlet and outlet samples (24 h composite sampling) were collected one to four times a month for a total of 13 samples per mesocosm. The following variables were measured according to standard methods (APHA 1998): COD, NO_3-N, NH_4-N, and PO_4-P. Evapotranspiration was estimated on every sampling date by measuring the total inflow and outflow. Removal efficiencies were calculated based on mass balance.

2.4 Modeling

Treatment of hydroponics wastewater by HSSF CWs should be primarily based on the removal of nitrogen rather than organic carbon as the latter is intentionally added to stimulate denitrification. Hence, treatment performances for nitrogen were simulated using a first-order kinetic plug flow model (Kadlec and Wallace 2008) to estimate the effect of carbon and plant species on degradation kinetics:

$$\frac{Cs}{Co} = e^{(-K_{VT}\cdot\tau)} \tag{1}$$

$$K_{VT} = K_V \times (\theta)^{\left(T_{avg}-20\right)} \tag{2}$$

- Cs mass flow at outlet (milligrams per day)
- Co mass flow at inlet (milligrams per day)
- K_{VT} first-order volumetric rate constant at temperature T° (day^{-1})
- τ experimental residence time distribution (day)
- K_V first-order volumetric rate constant at 20°C (day^{-1})
- T_{avg} average daily air temperature (°C)
- θ empirical abiotic constant, set to 1.06 following Rousseau et al. (2004).

Experimental results were fitted using this model with T_{avg}=8°C and gravel porosity=30%. Evapotranspiration was taken into account as mass flow was used instead of concentration. We calculated K_{V20} for total Nitrogen (TN) = (NO_3-N + NH_4-N), NO_3-N, and NH_4-N removal for systems with added carbon as they were the only ones with satisfactory N removal. R^2 were also computed between observed values and those predicted by the model to evaluate goodness of fit.

3 Statistical Analyses

We used a two-way repeated-measures analysis of variance (ANOVA) followed by a test of multiple comparisons of means (Tukey HSD) to test the effects of macrophytes species and carbon addition. All variables met the normality assumptions, and a square-root-transformation was applied to reduce the heterogeneity of the variances for COD. However, ANOVA was not performed for NH_4-N because no data transformation could adequately reduce the heterogeneity of the variances, except rank transformation, which is not recommended for designs including interactions (Quinn and Keough 2003). Statistical tests were considered significant at the 0.05 level and were performed with SPSS 16.0 statistical software.

4 Results and Discussion

4.1 Nitrate Removal

Nitrate removal from hydroponics wastewater under winter conditions ranged from 4% (*P. australis* no carbon) to 79% (*P. arundinacea* with carbon). Carbon addition had a highly significant impact on nitrate removal ($F_{1,8}$=1,607.7, P<0.001) in all treatments, with outlet concentrations three times lower and removal efficiencies ten times higher when carbon was added (Table 1). Planted mesocosms had slightly higher nitrate removal than unplanted controls with carbon addition, but removal was similar without carbon addition (Table 1). Wetlands planted with *P. arundinacea* removed more nitrate than wetlands planted with *P. australis* regardless of carbon addition ($F_{3,8}$=4.4, P<0.05), whereas the other two other plant treatments did not differ from either *P. arundinacea* or *P. australis* (Fig. 1a).

Carbon addition was the main factor that influenced nitrate removal in our study, as it greatly increased nitrate removal from a mean of 0.5 gN m^{-2} d^{-1} (no carbon) to 4.9 gN $m^{-2}d^{-1}$ (with carbon). However, even with the addition of carbon, denitrification was probably saturated as outlet nitrate concentrations remained high (range, 50 to 73 mg NO_3-N L^{-1}) and COD removal was almost complete (93% to 97%). This suggests that denitrification could be further stimulated by increasing the C/N ratio beyond the COD/N ratio used for this experiment (COD/N ratio, 3.5). This ratio was used by Lin et al. (2002), and they reported nitrate removal efficiencies higher than 90% compared to 69–72% for our system. This lower performance could be caused by greater competition for the added carbon between denitrifying bacteria and other wetland bacteria along with other factors (residence time, carbon source, and season). Therefore, the optimal COD/N ratio does not seem to be universal, and more ratios should be tested in order to optimize external carbon addition. As there is only a small range of COD/N ratio within which the effluent concentration of both nitrate and COD remain low (Park et al. 2008), finding the optimal ratio is a delicate but necessary task that remains to be done more exhaustively.

Although their effect was more subtle, plants also increased nitrate removal when carbon was added. Mesocosms planted with *P. arundinacea* were the most efficient but the differences were only margin-

Table 1 Inlet concentration, loading, and removal of pollutants expressed as percentage of removal according to plant presence (mean of all species) and carbon

				Planted		Unplanted	
		Loading (g $m^{-2}d^{-1}$)	Inlet (mg L^{-1})	Outlet (mg L^{-1})	Removal	Outlet (mg L^{-1})	Removal
Carbon	NO_3-N	6.90	228±7	65±20	72%	72±31	69%
	NH_4-N	0.51	17±2	6±3	68%	10±5	44%
	PO_4-P	1.68	57±4	40±10	30%	44±9	21%
	COD	24.68	814±55	28±12	97%	55±20	93%
No carbon	NO_3-N	6.84	225±8	211±24	7%	213±28	7%
	NH_4-N	0.52	16±2	6±3	63%	8±5	54%
	PO_4-P	1.73	58±3	52±7	10%	54±7	6%
	COD	0.70	24±8	15±9	33%	17±10	25%

Error values are standard deviations of the mean

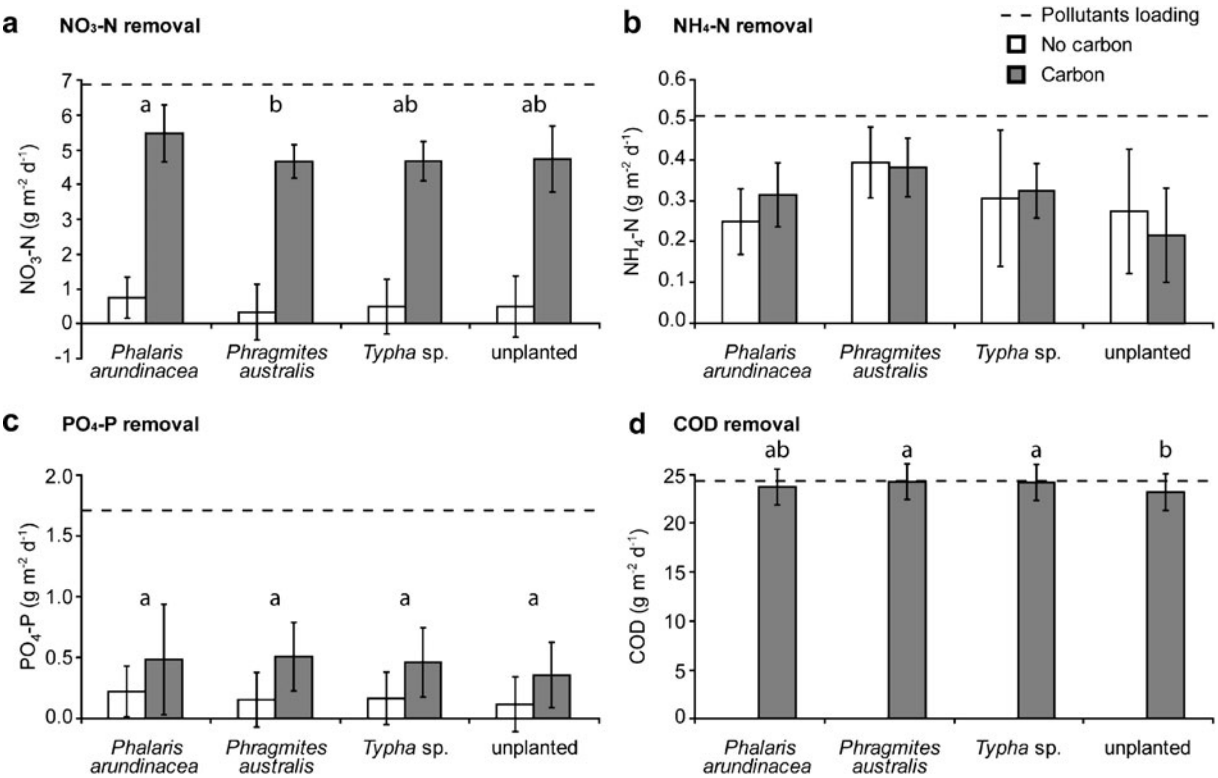

Fig. 1 Mean removal (in grams per square meter per day) according to plant species and carbon addition for **a** NO_3-N, **b** NH_4-N, **c** PO_4-P, and **d** COD. *Error bars* are standard deviations of the mean (n=13). *Lower case letters* represent a significant difference at α=0.05 among plant treatments following an ANOVA and Tukey HSD. COD removal without carbon is not represented in the figure because the values were extremely low compared with the removal found with carbon addition and could not be adequately represented in the figure (see Table 1 for details on inlet/outlet concentrations). ANOVA was not performed for NH_4-N because of the high heterogeneity of the variances

ally significant (P=0.042). Plants are thought to stimulate nitrate removal through plant uptake, but this should be negligible during the winter. Hence, the differentiation among plant species is more likely to be a function of carbon and oxygen availability. *P. arundinacea* has a shallow (but dense) root system (Gagnon et al. 2007). The larger culms and below-ground structures of *Typha* sp. and *P. australis* could result in higher oxygen diffusion from their cut stumps to the rhizosphere, which may partially inhibit denitrification. Also, *P. arundinacea* may release higher quantities of carbon through root exudates and decaying biomass (Zhu and Sikora 1995), which could stimulate denitrification.

The relative effect of plants is further supported by K_{V20} values for NO_3, which were highest with *P. arundinacea* and lowest with *Typha* sp. (Table 2). As NO_3 was the dominant species of nitrogen in this study, the pattern among treatments in K_{v20} values for TN is similar to that of NO_3 (Table 2). Overall, the kinetic rate observed for NO_3 removal was up to ten times greater compared with others studies conducted in horizontal CWs, where K_{V20} for TN ranged from 0.06 to 0.16 day^{-1} (Rousseau et al. 2004). This suggests that denitrification was the main biological path for TN and COD removal in our experiment. Values of K_{V20} also highlight that CWs planted with *P. arundinacea* would be more efficient per unit area than other plant treatments and could be the species of choice for this effluent given the large quantities of wastewater generated by the hydroponics industry.

4.2 Ammonium Removal

No statistical test could be performed for ammonium: interpretation of the results should be considered with care as they are based only on visual examination of the patterns (Fig. 1b). Planted mesocosms removed

Table 2 K_{V20} (day^{-1}) values for TN (NO_3+NH_4), NO_3, and NH_4 according to plant treatments in wetlands with carbon addition

	P. arundinacea	*P. australis*	*Typha* sp.	Unplanted
TN	1.13 (0.80)	0.88 (0.94)	0.85 (0.91)	0.91 (0.71)
NO_3	1.16 (0.77)	0.87 (0.93)	0.85 (0.90)	0.96 (0.68)
NH_4	0.67 (0.71)	1.05 (0.94)	0.72 (0.85)	0.37 (0.64)

R^2 values between observed and predicted values are given in parentheses

more ammonium than unplanted controls, and removal efficiencies ranged from 44% (unplanted with carbon) to 79% (*P. australis* no carbon) depending on conditions. Regardless of carbon addition, *P. australis* seemed to perform better than other plant treatments. Also, carbon addition appears to stimulate slightly NH_4 removal in planted mesocosms (increase from 63% to 68%) and reduced NH_4 removal in unplanted mesocosms (decrease from 54% to 44%; Table 1).

Higher ammonia removal in planted wetlands is often attributed to the enhancement of nitrification via root oxygen release and direct ammonia uptake by plants (Tanner et al. 2002), but plant uptake should be negligible in winter as it was for nitrate. As ammonia removal appears to vary among plant species—*P. australis* being the most efficient—this suggests that oxygen availability in the wetland matrix differs as a function of plants species (Stottmeister et al. 2003), even during winter. A differential oxygen release capacity among plants also supports the pattern we found among plants for NO_3 removal, and K_{V20} values for NH_4 (Table 2). Indeed, K_{V20} values were highest for *P. australis* and lowest for unplanted wetlands. Also, while *P. arundinacea* was the most efficient treatment at removing NO_3, it was the least efficient plant to remove NH_4. This suggests that species choice in CWs should be dependent on N speciation in the wastewater, as not all plants are equally efficient at all stages of treatment or all seasons. Our results also suggest that using different plants at different stages of treatment could optimize nitrogen removal if reduced N forms (organic or NH_4) are dominant. For example, *P. australis* could be used to stimulate nitrification in a first CW, and *P. arundinacea* could be used to stimulate denitrification in a second CW, at least in winter conditions.

Carbon addition generally enhanced ammonia removal in planted mesocosms, whereas it reduced ammonia removal in unplanted controls. Lower ammonia removal in unplanted mesocosms was expected as lack of plant-mediated oxygen release and high competition for oxygen between ammonia oxidizing and heterotrophic bacteria at high COD concentrations may inhibit nitrification (Michaud et al. 2006). However, the increase in ammonia removal with carbon addition in planted mesocosms does not follow classical trends in nitrification but could be due to an alternative process, heterotrophic nitrification, where the oxidation of ammonium is achieved by heterotrophic bacteria (Tanner et al. 2002). Increased ammonia removal with higher COD concentration was reported by Riley et al. (2005) in winter conditions and was attributed to increased plant-mediated oxygen availability in winter versus summer. Furthermore, the intensity of root oxygen release seems to be controlled by the external oxygen demand of the rhizosphere, with higher oxygen release rates in lower redox conditions (Wiessner et al. 2002). Therefore, higher oxygen availability at higher COD concentration could favor ammonia oxidizing bacteria and lead to higher ammonia removal when carbon is added to planted systems.

4.3 Phosphate Removal

Phosphate removal ranged between 6% (unplanted with no carbon) and 30% (*P. australis* with carbon), and planted mesocosms had slightly higher phosphate removal than unplanted controls (Table 1). We found no statistical difference in phosphate removal among plants species, with or without carbon addition (Fig. 1c). Regardless of plant treatment, mesocosms supplemented with carbon had significantly higher phosphate removal ($F_{1,8}$=136.9, P<0.001) than mesocosms with no carbon supply (Fig. 1c).

Although carbon addition enhanced phosphate removal from a mean of 0.2 gP m^{-2}d^{-1} (no carbon) to 0.5 gP m^{-2}d^{-1} (with carbon), outlet concentrations remained high with an average of 41 mg PO_4-P L^{-1}. Phosphorus removal is generally attributed to physical and chemical processes in HSSF CWs, with pH and redox often playing key roles (Vymazal 2007; Watson et al. 1989), although microbial uptake and storage can also be important (van Rijn et al. 2006). Indeed, the substantial addition of organic carbon (24.42 g COD m^{-2}d^{-1}) given to some mesocosms may have stimulated phosphate removal by promoting the growth of heterotrophs and the sequestration of phosphorus in microbial biomass. On the contrary, mesocosms not supplemented in carbon may have experienced relatively limited microbial growth and consequently lower phosphorus removal. This is supported by Park et al. (2008) who attributed high phosphorus removal in denitrification filters with added carbon to storage in denitrifying bacteria. However, high carbon availability seems to be important for high P bacterial retention as Huett et al. (2005) reported that phosphorus removal was unaffected by external carbon addition with a COD supply about 800 times lower than ours. Furthermore, microbial phosphorus sequestration is often considered as a short-term sink, as a substantial fraction of this phosphorus may be released at death (Vymazal 2007). Nevertheless, the production of refractory organic compounds of bacterial origin may lessen phosphorus release, due to the extremely slow biodegradation of these compounds (Gachter and Meyer 1993), thus contributing to sustained removal of phosphorus.

Apart from carbon addition, plant presence also had a slightly positive effect on phosphate removal (Table 1). As phosphorus uptake by plant may be assumed to be negligible in winter, the contribution of macrophytes to phosphorus removal in our experiment was probably due to the indirect effect of plants on bacteria and redox.

4.4 Chemical Oxygen Demand

COD removal ranged from 24% (*P. australis* no carbon) to 97% (*Typha* sp./*P. australis* with carbon), and plant presence stimulated COD removal, regardless of carbon addition (Table 1). Mesocosms planted with *Typha* sp. or *P. australis* had significantly higher COD removal than unplanted controls ($F_{3,8}$=7.8, P< 0.05), whereas *P. arundinacea* was intermediate and not statistically different from the other plant treatments (Fig. 1d). Mesocosms supplemented with carbon had near-complete COD removal (93% to 97%) and logically removed significantly more COD than the ones with no added carbon ($F_{1,8}$=60.3, P<0.001; Table 1). This near-complete COD removal at high concentrations (COD, 24.42 g m^{-2}d^{-1}) reflects the high biodegradability of our carbon source, sucrose.

Higher COD removal in planted mesocosms has been reported previously (Ouellet-Plamondon et al. 2006), and the difference between plants species could be explained by specificity of root oxygen release (Stottmeister et al. 2003). The lower efficiency of *P. arundinacea* for COD removal may also be attributed to a greater carbon release, through production of root exudates (Zhu and Sikora 1995) or decaying biomass. Finally, the COD fluctuation at the outlet of the mesocosms without added carbon, between 13–25 mg L^{-1}, can be attributed to normal organic carbon release by wetlands (Riley et al. 2005).

5 Conclusions

Planted wetlands with added organic carbon represent the best combination for hydroponics wastewater removal, with winter pollution removal averaging 72%, 68%, 30%, and 97% for nitrate, ammonium, phosphate, and COD, respectively. Also, wetlands planted with *P. arundinacea* were the most efficient at removing nitrate, likely as a function of higher carbon exudation and lower oxygen availability compared with other plants. Because pollutant removal in CWs is typically equal or higher in summer, our results confirm the efficiency of CWs for year-round treatment of hydroponics wastewater.

As in many other parts of the world, there is no unique effluent standard for hydroponics wastewater in the province of Quebec (Canada), each discharge requirement being determined individually based on the capacity of the receiving environment. Our experiment showed that pollutant removal of hydroponics wastewater by HSSF CWs remains important even under winter conditions. Nevertheless, phosphate concentrations at the CWs' outflow were still too high to reach most performance goals, indicating that other phosphorus removal systems must be considered. CWs greatly reduced nitrate discharge, with a mean of 50 mg NO_3-N L^{-1} at the outflow of CWs planted with *P. arundinacea* and supplemented with carbon. Increasing the C/N ratio could be an efficient way to further enhance nitrate removal, if needed, as carbon seems to remain limiting in our experiment.

Although interesting from a mechanistic perspective, the addition of sucrose (refined sugar) to wastewaters cannot be recommended in full-scale HSSF CWs because the energy input is too high and contradicts the extensive nature of CWs. As the addition of carbon had a significant beneficial impact, further research should focus on investigating the effects of other carbon sources whose production is less energy-intensive than sucrose.

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