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Maximizing pollutant removal in constructed wetlands: Should we pay more attention to macrophyte species selection?

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ABSTRACT

While the positive role of macrophytes on removal efficiency in constructed wetlands has been well established, possible differences in performance between plants species of comparable life forms and sizes are much harder to demonstrate. We reviewed 35 experimental studies published in peer-reviewed journals and proceedings on the effect of macrophyte species selection on pollutant removal in SSFCW. The studies cover a wide range of macrophyte species, experimental approaches (from well-replicated microcosm experiments to comparison between full full-size constructed wetlands), climatic conditions (from tropical to cold-temperate) and types of effluent (domestic, industrial, etc.). Frequent methodological limitations in these studies compel caution in the interpretation of their results. Yet, the fact that the majority found some (occasionally large) differences in efficiency between plant species for one or more type of pollutant suggests that macrophyte species selection does matter. However, there is little generalization to be made that could help guide species selection for SSFCW, except for the exact conditions in which the experiments were done. For example, the same pair of species that was tested in different studies occasionally gave opposite results in terms of which one performs best. Also, most studies provided few insights on the mechanisms or plant properties that could explain the observed differences in plant species efficiency. Finally, we discuss other relevant research questions and approaches that could help better guide macrophyte species selection for CW.

1. Introduction

Most studies comparing planted versus unplanted subsurface flow flow-constructed wetland system for wastewater treatment (SSFCW) show a significant and positive effect of macrophytes on pollutant removal (Tanner, 2001). Indeed, the role of macrophytes as an essential component of constructed wetland is well established (Brix, 1997; Stottmeister et al., 2003). For example, macrophytes provide a large surface area for attached microbial growth and supply reduced carbon and oxygen in the rhizosphere. They decrease current velocity, stabilize the surface of the bed, and insulate the surface against frost in winter.

If the benefits of the presence of macrophytes have been repeatedly demonstrated, it remains unclear whether there are significant differences in removal efficiency among plant species of comparable life forms and sizes. At present, macrophyte species selection for a specific CW is based

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more on established practices than on rigorous comparative assessment of efficiency among different species. Species are assumed to be adequate as long as they have fast growth rate, rapid establishment usually by clonal propagation, large biomass with a well developed belowground system, and good tolerance to CW conditions. There is nevertheless a growing number of published scientific papers that aim to compare the effect of two or more plant species on pollutant removal, but to our knowledge, there is no comprehensive assessment or generalization of their findings. Overall, do they commonly find differences between species in removal efficiency? If so, are these differences worth considering when weighted against other criteria for plant selection ? Are there plant species that perform consistently better than the others ? In summary, should we pay more attention to species selection in subsurface constructed wetland?

Here we review the published evidence on the effect of macrophyte species selection on pollutant removal in constructed wetland. We focus on published experimental studies comparing pollutant removal efficiency for two or more rooted macrophyte species, each growing in monocultures under the same exact CW experimental conditions. There are other approaches that guide species selection and provide indirect measures of removal efficiency. One of these approaches is to measure plant growth and pollutant-nutrient stored in plant tissue under CW conditions as an estimate of potential removal, without measures of influent-effluent removal (DeBusk et al., 1995). However, since plant accumulation is only one mechanism — often considered minor in SSCW — responsible for pollutant removal (Mander et al., 2003), we considered only studies measuring wastewater influent-effluent because they provide the most convincing evidence of species differences in removal efficiency.

2. Studies selection

The studies were selected first using the search engine of ISI Web of Knowledge with “constructed wetland” or “treatment wetland” and “plant” as keywords. We also examined thoroughly all specialized edited books and international conference proceedings on the subject, starting with the First International Conference on Constructed wetlands for Wastewater Treatment held in Chattanooga, Tennessee, in 1988 (Hammer, 1989). The studies were selected according to the following criteria: 1) a comparison was made between two or more species of rooted, emergent macrophytes, each grown in monocultures in side-by-side identical units (microcosm to full-size CW), with or without replicates or control (unplanted units); 2) our emphasis was on SSCW, but we did include studies using surface CW as long as the plants were rooted in a substrate that may contribute to removal. The only difference is that, in the latter case, the water is above rather than below ground level. Several of these studies use the same plant species as the one in strict SSCW. We did not consider studies comparing floating macrophytes in surface (free-water) constructed wetland, or with macrophytes growing under hydroponics conditions; 3) each unit had to receive the exact same treatment (type of wastewater, loading, etc.). Several studies examined one other variable, such as loading rates, in addition to species effect in a factorial design. Occasionally, units with different treatments (other than species) were pooled if that treatment had no measurable effect; 4) species efficiency had to be measured in terms of their effect on pollutant removal, either in terms of mass or concentration, based on inlet vs outlet characterization of each planted monoculture unit; 5) finally, we excluded studies that considered exclusively heavy metal removal because of the distinction between the mechanisms involved (bioaccumulation, precipitation) and management strategy for removal (plant harvesting) compared to the removal of other, more common types of pollutants involved in wastewater treatment.

We found 35 experimental studies matching our criteria, most of which published in the 2000s (Table 1). In two cases, we treated as separate studies two experiments that were presented in the same paper (# 14, # 15; and # 21, # 22: see Table 1 for study identification numbers), while in another case, we combined two papers that presented different aspects of the same experiment (# 13, 26). Also, we kept as separate, studies using the same experimental units with the same plants, but performed at different times under different experimental conditions (# 13, # 30; # 17, # 24, # 25; and # 26, # 27, # 28).

3. Experimental settings

From 2 to 8 species were tested in each study (Table 1). More than 70% of the studies also included unplanted, control units. The total number of macrophyte species covered is 48, although it may have been slightly more since in two cases (studies # 3 and # 31), the species were only identified to genus level. The most common species studied are *Typha latifolia* in 14 studies, followed by *Phragmites australis* in 13 studies, and *Schoenoplectus validus* (syn. *Scirpus validus*) and *Typha angustifolia*, each in 6 studies (Table 2). More than half of the macrophytes species were tested in only one study. While several of the studies dealt with tropical macrophytes, most covered species found under temperate climates.

Nearly half of the studies were performed in microcosms — buckets or columns — with at most a few plants per unit (Table 1). A majority of these microcosms were operated as batch reactor. Using microcosms is cheaper and allows both a larger number of species to be tested and/or adequate replication. However, results from microcosm experiments must be interpreted with care due to edge and container effects (Fraser and Keddy, 1997). For example, plants in microcosms do not experience the effect of neighboring plants on light interception and growth allometry. More importantly, root dispersion is often strongly affected, with proportionally more roots crowded along the inner surface of the recipient. For these reasons, microcosms are especially useful in determining broad patterns and investigating mechanisms. For application purposes, the value of the parameters measured in microcosm experiments should be validated under more realistic conditions. Only 7 studies were realized in large, full-scale or pilot-scale CW, 5 of which used a surface-flow design. They provide the most realistic conditions and, consequently, the most reliable results in terms of application,

Table 1 – Some methodological details of the experiments selected.

Study #	Authors	Location	Types of CW [a]	Size [b]	Nb of species	Other treatments [c]	Replication [d]	Control [e]
1	Abira et al. (2003)	Africa	BR	Micro	4	HRT (2), Wastewater (2)	2	Y
2	Akratos and Tsihrintzis (2007)	Europe	HSSF	Meso	2	Loading rate (2) (T)	1	Y
3	Bachand and Horne (2000)	N. Amer.	SF	Large	2	Mixed-species (1)	2	N
4	Bojcevska and Tonderski (2007)	Africa	SF	Large	2	Loading rate (2)	2	N
5	Calheiros et al. (2007)	Europe	HSSF	Meso	5	Loading rate (2) (T)	1	Y
6	Coleman et al. (2001)	N. Amer.	SSF	Meso	3	Depth (2)	2	Y
7	da Motta Marques et al. (2000)	S. Amer.	HSSF	Meso	2	Loading rate (2)	3	Y
8	DeBusk et al. (1992)	N. Amer.	HSSF	Large	2	Wastewater (2)	2	Y
9	Fraser et al. (2004)	N. Amer.	BR	Micro	4	Nutrient load (2)	6	Y
10	Gersberg et al. (1986)	N. Amer.	SF?	Large	3	N	1	Y
11	Haule et al. (2002)	Africa	HSSF	Meso	6	N	1	Y
12	Heritage et al. (1995)	Oceania	VSSF	Meso	4	N	1	Y
13	Hook et al. (2002); Allen et al. (2002); Stein et al. (2006)	N. Amer.	BR	Micro	3	N	8	Y
14	Huang et al. (2000a)	N. Amer.	HSSF	Micro	2	Loading rate (3)	2	N
15	Huang et al. (2000b)	N. Amer.	SF	Large	2	N	2	N
16	Inamori et al. (2007)	Asia	BR	Micro	2	Loading rate (3)	2	N
17	Jing et al. (2002)	Asia	SF	Micro	3	Loading rate (4)	1	Y
18	Juwarkar et al. (1995)	Asia	VSSF	Micro	2	N	?	Y
19	Kantawanichkul et al. (2005)	Asia	Dual HSSF and VSSF	Meso	2	N	1	N
20	Kim and Geary (2001)	Oceania	BR	Micro	2	Substrate (2)	5	N
21	Klomjek and Nitisoravut (2005)	Asia	SF	Meso	8	N	3	Y
22	Klomjek and Nitisoravut (2005)	Asia	SF	Meso	2	Loading rate (2)	?	N
23	Kuehn and Moore (1995)	N. Amer.	SF	Large	2	N	2	Y
24	Lin et al. (2002)	Asia	SF	Micro	3	N	1	Y
25	Lin et al. (2007)	Asia	SF	Micro	3	N	1	Y
26	Maltais-Landry et al. (2007) Chazarenc et al. (2007)	N. Amer.	HSSF	Meso	2	Loading rate (3) Forced aeration (y/n)	1	Y
27	Naylor et al. (2003)	N. Amer.	HSSF	Meso	2	N	4	Y
28	Ouellet-Plamondon et al. (2006)	N. Amer.	HSSF	Meso	2	Forced aeration (y/n)	2	Y
29	Picard et al. (2005)	N. Amer.	BR	Micro	4	Insolation level (2)	6	Y
30	Riley et al. (2005)	N. Amer.	BR	Micro	2	N	4	Y
31	Solano et al. (2004)	Europe	SSF	Large	2	Loading rate (2)	1	N
32	Tanner (1996)	Oceania	BR	Micro	8	N	3	N
33	Ujang et al. (2005)	Asia	SSF	Micro	2	Heavy metal load (2)	1	Y
34	Yang et al. (2007)	Asia	SF	Meso	5	N	3	Y
35	Zhu and Sikora (1995)	N. Amer.	BR	Micro	4	Nutrient load (2)	3	Y

[a] Type of CW. VSSF: vertical subsurface flow; HSSF: horizontal subsurface flow; SSF: subsurface flow; SF: free-water, surface flow; BR: batch reactor.

[b] Size of experimental units (surface area). Micro: microcosms (columns, buckets) < 0.5 m^2; Meso: mesocosm, from 0.51 to 5 m^2, large: pilot-scale and full-size CW>5 m^2.

[c] Other treatment, simultaneously in a different set of experimental units, or in the same units but at different times (*T*).

[d] Replication: number of units per species per treatment. One (1) means no replication.

[e] Control: presence of unplanted control (yes/no).

but their cost rarely allows sufficient replication or a large number of plant species to be tested. The remaining experiments were done in mesocosms (medium size units), which provides a compromise between the realism of full-scale experiments and the flexibility and low costs of microcosms. Most mesocosms were designed as subsurface, either vertical or horizontal flow, constructed wetlands (Table 1).

Because ecological systems are inherently variable, replicating the experimental units allows statistical testing and increases confidence that the differences detected in pollutant removal are systematic and due to the treatment (plant species). Most studies had little or no replication, and only a few were well-replicated experiments (from 5 to 8 replicates), all using microcosms (# 9, # 13, # 20, # 29). In several studies, the statistical comparisons of removal efficiencies among plant species were based on repeated measures within the same units rather than between sets of units with the same plant species. While significant differences between units solely based on repeated measures are often interpreted as being caused by the different plant species, this is not as strong as evidence as significant differences based on replicated units in an appropriate experimental design.

The effect of loading rates was the most common factor evaluated along plant species. Two or more loading rates were either evaluated simultaneously with plant species in a factorial experimental design (with or without replicates) or by modifying loading rates over time in the same units and comparing the different time series.

Table 2 – Macrophyte species studied.

Species name	Common name	Code	Study # (see Table 1)
Baumea articulata	Jointed rush	Baa	12,20,32
Bolboschoenus fluviatilis	River bulrush	Bof	32
Canna indica	Indian shot	Cai	5,34
Carex lacustris	Hairy sedge	Cal	9,29
Carex rostrata	Beaked sedge	Car	13,30
Commelina communis	Asiatic dayflower	Coc	17,24
Cyperus corymbosus	Jointed flat sedge	Cyc	21
Cyperus dubius	No common name	Cyd	11
Cyperus grandis	No common name	Cyg	11
Cyperus immensus	No common name	Cym	1
Cyperus involucratus	Umbrella plant	Cyn	12,32
Cyperus papyrus	Papyrus	Cyp	1,4
Digitaria bicornis	Asian crabgrass	Dib	21,22
Echinochloa pyramidalis	Antelope grass	Ecp	4
Echinodorus cordifolius	Creeping burhead	Ecc	21
Eriocaulon sexangulare	No common name	Ers	33
Glyceria maxima	Reed mannagrass	Glm	32
Iris pseudacorus	Paleyellow iris	Irp	5
Juncus effusus	Common rush	Jue	6,32
Kyllinga erectus	Greater kyllinga	Kye	11
Leptochloa fusca	Malabar sprangletop	Lef	21
Ludwigia octovalvis	Mexican primrose-willow	Luo	17
Pennisetum purpureum	Elephant grass	Pep	24,25,34
Phalaris arundinacea	Reed canarygrass	Pha	9,29,35
Phragmites sp.	Reed	Phs	31
Phragmites australis	Common reed	Phr	2,5,10,16,17,24,25,26,27,28, 32,34,35
Phragmites mauritianus	No common name	Phm	1,11
Phragmites vallatoria	Tropical reed	Phv	18
Sagittaria latifolia	Broadleaf arrowhead	Sal	8
Schoenoplectus acutus (Syn. *Scirpus acutus*)	Hardstem bulrush	Sha	13,23
Schoenoplectus mucronatus (Syn. *Scirpus mucronatus*)	Bog bulrush	Shm	20
Schoenoplectus pungens (Syn. *Scirpus pungens*)	Common threesquare	Shp	8
Schoenoplectus validus (Syn. *Scirpus validus*)	Softstem bulrush	Shv	6,9,10,12,29,32
Scirpus sp. or *Schoenoplectus* sp.	Bulrush	Scs	3
Scirpus atrovirens	Green bulrush	Sca	35
Scirpus cyperinus	Woolgrass	Scc	14,15
Scirpus globulosus	No common name	Scl	33
Scirpus grossus	Greater club rush	Scr	19
Spartina patens	Saltmeadow cordgrass	Spp	21
Stenotaphrum secundatum	St. Augustine grass	Sts	5
Typha sp.	Cattail	Tys	3,31
Typha angustifolia	Narrowleaf cattail	Tya	19,21,22,26,27,28
Typha capensis	No common name	Tyc	11
Typha domingensis	Southern cattail	Tyd	1,11
Typha latifolia	Broadleaf cattail	Tyl	2,5,6,9,10,13,14,15,18,23,29,30,34,35
Typha orientalis	Broadleaf cumbungi	Tyo	12,25
Typha subulata	No common name	Tyu	7
Urochloa mutica	Para grass	Urm	21
Vetiveria zizanoides	Vetiver	Vez	21,34
Zizania latifolia	Manchurian wildrice	Zil	16,32
Zizaniopsis bonariensis	No common name	Zib	7

Common names were searched from different web plant databases, consulted in April 2008, especially USDA plant database (http://plants.usda.gov/), Florabase (http://florabase.calm.wa.gov.au/); Germplasm Resources Information Network Taxonomy for Plants (www.ars-grin.gov/cgi-bin/npgs/html/queries.pl).

Although most studies used real or synthetic domestic and municipal wastewater, other sources of wastewater were also tested: paper-mill (# 1, # 23), tannery (# 5), fish-farm (# 26, # 27, # 28), and pig-farm (# 19). Other experimental conditions that varied among experiments and that may influence results are the length and season of the experimental survey and the age of the wetland at the time of the experiment (from a few weeks after seedling establishment to several years). It is important to verify these conditions when looking for insights from a particular study for species selection for a real application.

The most common pollutant types used to evaluate the efficiency in removal were total suspended solids (TSS), organic matter (COD or BOD), total nitrogen (TN), ammonium (NH_3) and nitrate (NO_3), total phosphorus (TP) and phosphate (PO_4).

4. Species comparisons

The large majority of the studies found a difference in efficiency between macrophyte species, for one or more pollutants (Table 3). In a few cases, these differences (or lack of difference) should be interpreted with care since the authors reported problems in macrophyte growth or health, either due to wastewater toxicity (# 9, # 10, # 16, # 21), matrix pH (# 5, # 27), unpredictable events such as exceptional freezing (# 8) or herbivory (# 23), or other unspecified reasons (# 9, # 11, # 31). While these results may provide valuable information on plant species tolerance to specific constructed wetland conditions, reported differences in removal efficiency for species of low health or insufficient growth give an unfair assessment on the real relative species contribution in removal. Besides health, the time since establishment is also a factor that may influence removal. A fair comparison should involve mature plants, but in a few cases, the experiments were realized while the macrophyte cover was probably still immature, at least for one or more species. For example, it is reported that *P. australis* may take up to 3 years before reaching maturity (Vymazal and Kröpfelová, 2005), so that using a younger plant cover may underestimate the real efficiency of this species in a constructed wetland meant to last several decades. Yet, even when only considering studies involving mature, healthy macrophyte species of comparable growth form, differences in removal efficiency are frequent (Table 3), and these differences are anything from small to large, up to double in removal in certain circumstances.

When there was a difference in removal between plant species, this difference appears to involve more often nitrogen removal (especially nitrate) and less so suspended solids and organic matter, with no clear trends for phosphorus (for example, see Table 3: # 2, # 4, # 12, # 16, # 32, # 34). This is not surprising since the same trend has been repeatedly observed in planted–unplanted experiments (Tanner, 2001). For example, nitrogen removal is known to be influenced by the presence of plants, either directly through assimilation or indirectly through the influence of plants on oxygen and microbial activity in the matrix. On the other hand, plants contribute little to suspended solid removal in subsurface constructed wetlands since the primary mechanisms involved are filtration and sedimentation (IWA, 2000). Macrophytes may play a role in free-water surface wetland by dampening current velocities and wave energy, thus allowing suspended sediments to settle out. However, there were few free-water surface systems in our review and most were probably too small for this process to occur.

Few species were tested in a number of studies sufficient enough to warrant an overall ranking in relative species efficiency. Even for the most tested species, the relative performance varied according to the pollutant considered, experimental design, type of wastewater, climate, etc. Therefore, different conclusions were sometimes drawn for studies comparing the same pair of species. The most common pair of species examined for their relative efficiency is *P. australis* and *T. latifolia* (# 2, # 5, # 10, # 34, # 35). *Phragmites* appeared more efficient in pollutant removal in # 10 and # 35; *Typha* was more efficient in # 2, and the remaining two studies found no

Table 3 – Relative difference in removal efficiency for different plant species, according to type of pollutant.

Study # (see Table 1)	Species differences (see Table 2 for species code)
1	SS: *Tyd*>*Cym*=*Cyp*=*Phm*
	COD: depend on HRT and type of wastewater
2	BOD, COD: no difference [a]
	TKN, NH_4, TP, PO_4: *Tyl*>*Phr*
3	NO_3: *Tys*>*Scs*
4	SS, TP, PO_4: no difference
	NH_4: *Cyp*>*Ecp*
5	For 7 pollutant parameters: no difference
6	BOD: *Tyl*>*Jue*=*Shv*
	TKN, NO_3: *Tyl*>*Jue*>*Shv*
	SS: no difference
7	NO_3: *Tyu*>*Zil*
	COD, NH_4, TN, TP, PO_4, SS: no sign. diff.
8	TP, TN: *Sal*>*Shp*
	BOD, TSS: no diff.
	At low nutrient level:TP, TN: *Shv*>*Tyl*=*Cal*>*Pha*
	At high nutrient level: depend on date
10	NO_3, NH_4, BOD: *Shv*>*Phr*>*Tyl*
	TSS: no diff.
11	TKN, NH_4*: *Kye*=*Tyd*=*Tyc*=*Phm*>*Cyd*=*Cyg*
	NO_3*: no diff.
12	TKN, NH_4, TP*: *Baa*>*Cyn*>*Tyo*>*Shv*
	BOD, SS*: no difference
13	COD: *Car*>*Sha*>*Tyl*
14	NO_3, TKN, NH_4: no difference
15	NO_3: *Tyl*>*Scc*
	TKN, NH_4: no difference
16	BOD, COD: no difference
	TN, NH_4, TP: *Zil*>*Phr* at high load only
17	PO_4, COD: no difference
18	TN, TP, DBO*: *Phv*>*Tyl*
19	For 8 pollutant parameters: no difference
20	TP: *Shm*>*Baa*
21	BOD, SS, TP, NO_3,NH_4: no difference [a]
22	BOD, sBOD, SS: *Dib*>*Tya*
23	TSS: *Tyl*>*Sha*
	BOD: no sign. difference
24	NO_3: *Pep*>*Phr*=*Coc*
25	NO_3: *Pep*=*Tyo*>*Phr*
26	COD, SS, TKN, TP: no difference
27	BOD, COD, SS, TKN, TP, PO_4: no difference
28	COD, SS, TKN: no difference
29	TDN: *Shv*=*Pha*=*Tyl*>*Cal*
30	NH_4: *Car*>*Tyl* (summer only)
	TN: *Tyl*>*Car* (winter only)
31	BOD, COD, SS: no significant difference
32	SS, BOD, TP: no significant difference
	TN: sign. differences, species not specified
33	BOD, COD: *Ers*>*Scg*
	SS: *Scg*>*Ers*
34	BOD, COD, TP: no difference
	TN (summer): Pep>Cai=Phr=Tyl=Vez
	TN (winter): Cai>Pep=Phr=Tyl=Vez
35	NH_4: *Phr*>*Pha*=*Sca*>*Tyl*
	NO_3: *Phr*=*Pha*>*Sca*=*Tyl*

[a] Our own interpretation of the results presented in the paper.

differences between these species (Table 3). The pair *T. latifolia* and *S. validus* was examined in four studies (# 6, # 9, # 10, # 29), one of them finding *Typha* to be more efficient than *Schoenoplectus* (# 6), two of them finding the opposite (# 9, # 10) and the last one (# 28) failing to find a difference (Table 3). For a pair of species, relative efficiency may vary according to pollutant or some other factor such as loading rate or seasons. For example, *Carex rostrata* was better than *T. latifolia* for ammonium removal in summer, but *Typha* was better at total nitrogen removal in winter (# 30). *Canna indica* was better than *Pennisetum purpureum* at total nitrogen removal in summer but the inverse was true in winter (# 34).

While the goal of this review was not to look at simple differences in efficiency between planted–unplanted constructed wetlands, the fact that 25 studies we considered also included unplanted units allowed us to do so. The advantage of planted over unplanted units for removal was unequivocal: all but one experiment found unplanted units to be less efficient than planted units, at least for one pollutant. The only study where removal was similar in planted and unplanted had very little healthy plants in the “planted” units because of severe growth problems and mortality due to the very high pH of the matrix (# 5).

5. Discussion

The scientific evidence for differences in removal efficiency between macrophyte species of comparable life forms varies from strong statistical inferences based on well-replicated controlled experiments to simple comparison of non-replicated units. The results may not always reflect exactly what would occur under real constructed wetland conditions since part of the differences reported could be due to the unavoidable shortcomings of experimental conditions (smaller unit size, reconstructed wastewater, immature macrophytes, etc.). Yet, while the results from several studies should be interpreted with care, the fact that the majority found a difference (occasionally large) in removal efficiency suggests that macrophyte species selection does matter.

In designing a specific constructed wetland, one can refer to experiments under comparable conditions and the results reported in Table 3 to select a plant species. Beyond that, our review failed to reveal any generalization that could guide species selection under any circumstances. Most species were tested only once or twice, precluding overall assessment of their relative efficiency. As for those tested more often, comparing the same pair of species lead to different results in terms of ranking depending on the experimental conditions, so that there is no one species coming undeniably as the best one in most circumstances.

There are obvious limitations in an approach based on experimental comparisons of pollutant removal for selecting the best plant species to use in a constructed wetland. The time required to achieve a complete experiment is substantial, and so is the cost, in particular if one has to start from plant establishment and grow mature colonies before starting measuring removal efficiencies over a certain period. Also, the number of species to be tested is necessarily limited, especially if one wants to use larger (and more costly) experimental units than microcosms. The ranking in species efficiency may not necessarily apply for other types of wastewater or conditions than the one tested. Even when applied within the same conditions, the ranking revealed under experimental units is likely to remain under full-size constructed wetland but the magnitude of this difference may not be the same. Finally, because of the empirical nature of the studies, the mechanisms explaining differences in removal between species remain mostly unknown.

Despite these limitations, we believe that experimental species comparisons such as those reviewed here are important in screening for new species or guiding species selection for a specific application. More rigorous experiments of this type, done under a variety of conditions, are still needed. Because of the inherent variation in complex ecological systems such as constructed wetlands, we recommend that replication in experimental units should be considered when possible, even at the expense of the number of species to be tested. Statistical differences based on well-replicated units in an appropriate experimental design increase confidence that they are due to differences in plant species and not by chance alone or some confounding factor (Quinn and Keough, 2002). Also, plant health should always be monitored and reported since a fair comparison between plant species should involve healthy, mature individuals. Plant size at a specific time is an obvious measure of plant health because it integrates plant performance over a long period of time. Other instantaneous parameters, such as leaf irradiance or gas exchange, if repeated in time, may suggest more specific physiological problems not revealed by size alone. Low growth or poor health may indicate that the species simply does not withstand well the specific conditions under which it was tested (type of wastewater, matrix, climate, etc.) in which case it is unsuitable for such constructed wetland. It can also stems from conditions unrelated to the operating conditions themselves or to inadvertent problems, such as diseases. In several studies reviewed here, it was not possible to determine if a plant species was intrinsically less efficient than the others or if its low efficiency was due to poor health since plant growth or vigor were rarely reported.

We suggest that future research incorporates the search for plant attributes that are good predictor of relative removal efficiency for significant progress to be made in selecting plant species and understanding the causes for the differences observed. For example, if plant size ranking was found to be highly correlated to removal efficiency ranking in most experiments, then one could eventually simply choose the plant that reaches the largest size under a specific wastewater application and climate. A simple test for plant selection would thus be to grow several species under the wastewater conditions and evaluate, after sufficient time, the predictor parameters, with no need to measure and compare pollutant removal. One of the goals we were pursuing while realizing this review was to examine if such attributes would emerge from the published literature. Unfortunately, even simple plant measures such as aboveground biomass are very rarely reported in comparison experiments, so that no such assessment was possible. One notable exception is # 32 (Tanner, 1996), where removal efficiency of eight species of macrophyte treating dairy farm wastewaters was compared in a microcosm experiment. Several parameters of shoot and root growth were monitored during the experimental period. At the end of the experiment, belowground and aboveground plant material was sampled and sorted into its different constituent parts (e.g. leaves, stems, rhizomes and roots) for biomass measurements. In this experiment, mean removal of total nitrogen was found to be linearly correlated to plant total biomass (Tanner, 1996). We strongly suggest that future comparison studies always include such plant measurements. Aboveground biomass, based on a sample of plant material collected at the end of the experiment, is simple to realize, does not require excavation and may serve as a basis for comparison between species. Some measures of belowground biomass should also be considered when possible since it may more likely reflect removal efficiency (however, in Tanner (1996), aboveground biomass was more strongly correlated to total nitrogen removal than belowground biomass). Other parameters that may be considered are root surface, because it is more directly related to the surface available for microbial colonization than biomass alone (Gagnon et al., 2007), and leaf surface area, because it may better reflect oxygen transport to the roots than plant biomass (Tanaka et al., 2007). Several physiological, morphological or biochemical factors play a role in a plant overall contribution to pollutant removal so it is unlikely that only one parameter would fully explain removal efficiency of a species in all circumstances. Yet, the inclusion of such types of measurements and search for patterns in comparison experiments would not only guide better future plant species selection, but it would also give insights into the mechanisms that make a plant better in contributing to water treatment.

As improvements in CW design reach a plateau, species selection may be the final best way to further maximize pollutant removal. In this review, we showed that plant species selection deserves better attention. We suggest that future research should go beyond the only empirical comparison in removal efficiency and aim at looking at patterns and mechanisms. In the future, it is conceivable that super-species or genotypes will be specifically selected for CW, as they are now in the related field of phytoremediation for heavy metal removal in contaminated soils.

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REFERENCES

Abira MA, Ngirigacha HW, van Bruggen JJA. Preliminary investigation of the potential of four tropical emergent macrophytes for treatment of pre-treated pulp and papermill wastewater in Kenya. Water Sci Technol 2003;48:223–31.

Akratos CS, Tsihrintzis VA. Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetland. Ecol Eng 2007;29:173–91.

Allen WC, Hook PB, Biederman JA, Stein OR. Temperature and wetland plant species effects on wastewater treatment and root zone oxidation. J Environ Qual 2002;31:1010–6.

Bachand PAM, Horne AJ. Denitrification in constructed free-water surface wetlands: II. Effects of vegetation and temperature. Ecol Eng 2000;14:17–32.

Bojcevska H, Tonderski K. Impact of loads, season, and plant species on the performance of a tropical constructed wetland polishing effluent from sugar factory stabilization ponds. Ecol Eng 2007;29:66–76.

Brix H. Do macrophytes play a role in constructed treatment wetland? Water Sci Technol 1997;35:11–7.

Calheiros CSC, Rangel AOSS, Castro PML. Constructed wetland systems vegetated with different plants applied to the treatment of tannery wastewater. Water Res 2007;41:1790–8.

Chazarenc FG, Maltais-Landry G, Troesch S, Comeau Y, Brisson J. Effect of loading rate on performance of constructed wetlands treating an anaerobic supernatant. Water Sci Technol 2007;56:23–9.

Coleman J, Hench K, Garbutt K, Sexstone A, Bissonnette G, Skousen J. Treatment of domestic wastewater by three plant species in constructed wetlands. Water Air Soil Pollut 2001;128:283–95.

da Motta Marques DML, Leite GR, Giovannini SGT. Performance of two macrophyte species in experimental wetlands receiving variable loads of anaerobically treated municipal wastewater. Water Sci Technol 2001;44:311–6.

DeBusk TA, Langston MA, Burgoon PS, Reddy KR. A performance comparison of vegetated submerged beds and floating macrophytes for domestic wastewater treatment. In: Cooper, PF, Findlater, BC, editors. Constructed wetlands in water pollution control. Wiltshire, UK: Pergamon press; 1992. p. 301–8.

DeBusk TA, Peterson JE, Reddy KR. Use of aquatic and terrestrial plants for removing phosphorus from diary wastewaters. Ecol Eng 1995;5:371–90.

Fraser LF, Keddy P. The role of experimental microcosms in ecological research. Trends Ecol Evol 1997;12:478–81.

Fraser LF, Carty SM, Steer D. A test of four plant species to reduce total nitrogen and total phosphorus from soil leachate in subsurface wetland microcosms. Bioresour Technol 2004;94:185–92.

Gagnon V, Chazarenc F, Comeau Y, Brisson J. Influence of macrophytes species on microbial density and activity in constructed wetlands. Water Sci Technol 2007;56:249–54.

Gersberg RM, Elkins BV, Lyon SR, Goldman CR. Role of aquatic plants in wastewater treatment by artificial wetlands. Water Res 1986;20:363–8.

Hammer DA. Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural. Chelsea, MI: Lewis Publ; 1989. 832 pp.

Haule AT, Pratap HB, Katima HJY, Mbwette TSA, Njau K. Nitrogen removal from domestic wastewater in subsurface flow constructed wetlands by indigenous macrophytes in the tropics: a comparative study for six potential macrophytes in Tanzania. In: Bwette, M, editor. Eighth IWA international conference on the use of constructed wetlands in water pollution control, 16–19 September, 2. ; 2002. p. 938–51. Tanzania.

Heritage A, Pistillo P, Sharma KP, Lantzke IR. Treatment of primary-settled urban sewage in pilot-scale vertical flow wetland filters: comparison of four emergent macrophyte species over a 12 month period. Water Sci Technol 1995;32:295–304.

Hook PB, Stein OR, Allen WC, Biederman JA. Plant species on seasonal performance patterns in model subsurface wetlands.

In: Mander, Ü, Jenssen, P, editors. Constructed Wetlands for Wastewater Treatment in Cold Climates. Southampton, UK: WIT Press; 2002. p. 87–105.

Huang J, Reneau RB, Jagedorn C. Nitrogen removal in constructed wetlands employed to treat domestic wastewater. Water Res 2000;34:2582–8.

Inamori R, Gui P, Dass P, Matsumura M, Xu KQ, Kondo T, et al. Investigating CH4 and N2O emissions from eco-engineering wastewater treatment processes using constructed wetland microcosms. Process biochem 2007;42:363–73.

International Water Association (IWA). Constructed wetland for pollution unplanted processes, performance, design and operation. Scientific and Technical Report, vol. 8. London, UK: IWA Publishing; 2000. 156 pp.

Jing SR, Lin YF, Wang TW, Lee DY. Microcosm wetlands for wastewater treatment with different hydraulic loading rates and macrophytes. J Environ Qual 2002;31:690–6.

Juwarkar AS, Oke B, Juwarkar A, Patnaik SM. Domestic wastewater treatment through constructed wetland in India. Water Sci Technol 1995;32:291–4.

Kantawanichkul S, Aekasin U, Shutes RBE. The comparison of *Scirpus* and *Typha* in a combined constructed wetland system. IWA Specialist Group on Use of Macrophytes in Water Pollution Control, Newsletter, vol. 26. ; 2005. p. 18–21.

Kim S-Y, Geary PM. The impact of biomass on phosphorus uptake by wetland plants. Water Sci Technol 2001;44:61–7.

Klomjek P, Nitisoravut S. Constructed treatment wetland; a study of eight plant species under saline conditions. Chemosphere 2005;58:585–93.

Kuehn E, Moore JA. Variability of treatment performance in constructed wetlands. Water Sci Technol 1995;32:241–50.

Lin YF, Jing SR, Lee DR, Chang YF, Shih KC. Nitrate removal and denitrification affected by soil characteristics in nitrate treatment wetlands. J Environ Sci Health 2007;42:471–9.

Lin YF, Jing SR, Wang TW, Lee DY. Effects of macrophytes and external carbon sources on nitrate removal from groundwater in constructed wetlands. Environ Pollut 2002;119:413–20.

Maltais-Landry G, Chazarenc F, Comeau Y, Troesch S, Brisson J. Effects of artificial aeration, macrophyte species and loading rate on removal efficiency in constructed wetland mesocosms treating fish farm wastewater. J Environ Eng Sci 2007;6:409–14.

Mander U, Teiter S, Kuusemets V, Lohmus K, Oeoevel M, Nurk K, et al. Nitrogen and phosphorus budgets in a subsurface flow wastewater treatment wetland. Water Resources Management II. Prog Water Resour 2003;8:135–48.

Naylor S, Brisson J, Labelle MA, Drizo A, Comeau Y. Treatment of fish farm effluent in Canada using CWS — highlighting the role of plants and substrate in nutrients removal. Water Sci Technol 2003;48:215–22.

Ouellet-Plamondon C, Chazarenc F, Comeau Y, Brisson J. Artificial aeration to increase pollutant removal efficiency of constructed wetlands in cold climate. Ecol Eng 2006;27:258–64.

Picard C, Fraser LH, Steer D. The interacting effects of temperature and plant community type on nutrient removal in wetland microcosms. Bioresour Technol 2005;96:1039–47.

Quinn GP, Keough MJ. Experimental Design and Data Analysis for Biologists. U.K.: Cambridge University Press; 2002. 537 pp.

Riley KA, Stein OR, Hook PB. Ammonium removal in constructed wetland microcosms as influenced by season and organic carbon load. J Environ Sci Health 2005;40:1109–21.

Solano ML, Soriano P, Ciria MP. Constructed wetlands as a sustainable solution for wastewater treatment in small villages. Biosyst Eng 2004;87:109–18.

Stein OR, Biederman JA, Hook PB, Allen WC. Plant species and temperature effects on the k-C first-order model for COD removal in batch-loaded SSF wetlands. Ecol Eng 2006;26:100–12.

Stottmeister U, Wießner A, Kuschk P, Kappelmeyer U, Kästner M, Bederski O, et al. Effects of plants and microorganisms in constructed wetlands for wastewater treatment. Biotechn Adv 2003;22:93–117.

Tanaka N, Yutani K, Aye T, Jinadasa KBSN. Effect of broken dead culms of *Phragmites australis* on radial oxygen loss in relation to radiation and temperature. Hydrobiologia 2007;583:165–72.

Tanner CC. Plants for constructed wetland treatment systems — a comparison of the growth and nutrient uptake of eight emergent species. Ecol Eng 1996;7:59–83.

Tanner CC. Plants as ecosystems engineers in subsurface-flow treatment wetlands. Water Sci Technol 2001;44:9–17.

Ujang Z, Soedjono E, Salim MR, Shutes RB. Landfill leachate treatment by an experimental subsurface flow constructed wetland in tropical climate countries. Water Sci Technol 2005;52:243–50.

Vymazal J, Krőpfelová L. Growth of *Phragmites australis* and *Phalaris arundinacea* in constructed wetlands for wastewater treatment in the Czech Republic. Ecol Eng 2005;25:606–21.

Yang Q, Chen ZH, Zhao JG, Gu BH. Contaminant removal of domestic wastewater by constructed wetland: effects of plant species. J Integra Plant Biol 2007;49:437–46.

Zhu T, Sikora FJ. Ammonium and nitrate removal in vegetated and unvegetated gravel bed micorcosm wetlands. Water Sci Technol 1995;32:219–28.