Criteria for determining alternative plants to improve the resource recovery efficiency in constructed wetlands

N. Chiarawatchai, M. Heers and R. Otterpohl

ABSTRACT

The aim of this study is to find the macrophytes that possess high resource recovery efficiency in subsurface-flow constructed wetlands (SFCWs) while not pose any negative effects to the treatment performance. Five criteria were included in this analysis. The suitable alternative plants were proposed according to their availabilities in each climate zone. For their potentials as an energy sources, they are related to plants' productivity as well as growth rate. Concerning the utilization options, plants that possess high economical value and/or versatilities were encouraged. Among the options are handicrafts, fertilizers, animal feeds, construction materials, paper making, and pharmaceutical products. In term of nutrient uptakes, in most cases they were relatively minor comparing to other removal mechanisms in SFCWs. No significant differences in term of treatment efficiency could be found. The proposed species have to be able to tolerate the municipal wastewater. The cost differences of plant propagules between each species are marginal, hence they should not be considered as the main selection criteria. Based on an investigation of 45 species worldwide, the recommendation table is developed with 13 suitable species that fit all the criteria. It appears that there are more than one "most appropriate plant species" in each climatic region. To perform the selection, the operators should weight their preferences on each criteria and the availability of plants in the area.

Key words | alternative plants, constructed wetlands, plant utilizations, resource recovery, wastewater treatment

N. Chiarawatchai
M. Heers
R. Otterpohl
Institute of Wastewater Management and Water Protection,
Hamburg University of Technology,
Eissendorferstrasse 42,
21073 Hamburg,
Germany
E-mail: *nathasith.chiarawatchai@tuhh.de*; *Martin.Heers@gmx.de*; *otterpohl@tuhh.de*

INTRODUCTION

Among several technologies applied to treat municipal wastewater, subsurface-flow constructed wetlands (SFCWs) is one of the popular options due to its nature-orientated concept as well as its lower cost and energy requirement comparing to the conventional ones. In the UK alone, there are approximately 1,000 units in operation (Cooper 2007). They can be classified according to the type of feed pattern as horizontal subsurface-flow constructed wetlands (HSFCWs) and vertical subsurface-flow constructed wetlands (VSFCWs) (Reed *et al.* 1995). As plants are one of the major components in both types of SFCWs, investigating their recovery potentials apart from their contribution to the treatment performance are of importance in order to make use of resources effectively.

Generally, common reed (*Phragmites Australis*) is among the most popular plants used in constructed wetlands because of high tolerance and it is abundant in several area of the world (Kadlec & Knight 1996). Nevertheless, the harvest of reed, which is generally conducted at the end of the growing season, has been of less focused. Open burning of plants after the harvest is a common practice at several SFCWs, which in term of nutrient recovery this method represents a waste of resource. Moreover, in several cases there is no harvest at all, such as the constructed wetlands in the Czech Republic (Vymazal 1996). Under these circumstances a major part of the nutrients that is accumulated by plants might be recycled to the water (or soil) again (Kadlec *et al.* 2000). Hence, it might be more economical and

doi: 10.2166/wst.2008.536

ecologically-sound if plants that possess more utilization options are used rather than the conventional ones so that the stakeholders can plan a use of it effectively. This can guarantee that the resources would not be wasted, instead will be appropriately used. This potential, if appropriately managed, could to some extent return the costs of the overall treatment system (Wissing & Hoffmann 2002). Furthermore, it could expand the possibilities to use other alternative plants in the area where no common wetland plant is available. Hence, the aim of this study was to propose the suitable alternative macrophytes that possess high resource recovery efficiency in SFCWs without any negative effects to the treatment performance.

METHODOLOGIES

As energy is one of the most serious issues nowadays, it was separated from the utilization options and was presented on its own as one of the consideration criteria. Still, the main purpose of constructed wetlands is to treat wastewater. Not all plant species that pose a high productivity or have other ancillary benefits are able to tolerate the hydraulic and high-loaded organic and eutrophic conditions typically found in constructed wetlands. Finally the costs to obtain such plants should not be overlooked. As a result, 5 criteria namely 1) potentials for energy sources, 2) plants utilization options, 3) nutrients uptake, in which all these three were directly related to the resource recovery aspect, 4) treatment performance and tolerance to inundation and the components in municipal wastewater, and 5) costs of plants were included in this analysis. Totally 44 species of plants were investigated based on hundreds of records in the literature (Heers 2006). The most suitable plants were proposed according to their availabilities in each climate zone, as generally temperate plants might not present in tropical climate.

RESULTS AND DISCUSSION

Investigated species in alphabetical order

Arundo donax (giant reed), *Baumea articulata* (jointed twig-rush), *Canna flaccida* (canna lily), *Canna indica* (Indian shot), *Carex acuta* (slender tufted sedge), *Carex aquatilis* (water sedge), *Carex fascicularis* (tassel sedge), *Carex rostrata* (beaked sedge), *Coix lacryma-jobi* (Job's tears), *Cyperus involucratus* (umbrella sedge), *Cyperus latifolius* (broad-leaved sedge), *Cyperus malaccensis* (Shichito matgrass), *Cyperus papyrus* (papyrus), *Eleocharis sphacelata* (tall spike rush), *Glyceria maxima* (reed sweet grass), *Juncus effusus* (soft rush), *Juncus ingens* (giant rush), *Lepironia articulata* (tube sedge), *Lolium perenne* (perennial ryegrass), *Miscanthus sacchariflorus* (Amur silver grass), *Miscanthidium violaceum* (Miscanthidium), *Pennisetum clandestinum* (Kikuyu grass), *Pennisetum purpureum* (Napier grass), *Phalaris arundinacea* (reed canary grass), *Phragmites karka* (tall reed), *Phragmites mauritianus* (Lowveld reed), *Scirpus acutus* (hard stem bulrush), *Scirpus californicus* (giant bulrush), *Scirpus cyperinus* (wool grass), *Scirpus grossus* (greater club rush), *Scirpus pungens* (Olney's bulrush), *Scirpus validus* (soft stem bulrush), *Scirpus lacustris* (common bulrush), *Scirpus maritimus* (alkali bulrush), *Typha angustifolia* (narrow-leaved cattail), *Typha capensis* (common cattail), *Typha domingensis* (southern cattail), *Typha latifolia* (broad-leaved cattail), *Typha orientalis* (broad-leaved cumbungi), *Typha subulata* (cattail, totora), *Vetiveria zizanioides* (vetiver grass), *Zizaniopsis bonariensis* (Espadaña), *Zizania latifolia* (Manchurian wild rice), *Zizaniopsis miliacea* (giant cutgrass)

Classification of climate types

The well known climate classification system according to Koeppen was used (Geiger 1961). However, as the classification was very complex, a simplification was necessary. In this study, the global climatic regions were divided according to the ranges of latitude, climate characters, and area applied. As a result, 6 zones were classified and summarized as shown in Table 1.

Criteria used to determine alternative plants

Potentials for energy sources

The potentials of plants as an energy source is presented based on the extensive investigation of both scientific literature and real case studies. It has been found that, due to the use of biomass as an energy source after harvest,

Table 1 | Classification of climate zone (N: North and S: South)

Climate classification	Latitude	Climate characters	Area applied	Abbreviation
Cold/boreal	50°–70° N/S	Long with very cold winter and short summer	Scandinavian Europe	NE
			Northern parts of North America	NNAm
		Highly varying seasonal temperature	Northern Asia (e.g. Siberia)	NAs
		Small annual precipitation		
Temperate	30°–55° N/S (Europe 45°–60°N)	Large seasonal changes between summer and winter	Central and Eastern Europe	CEE
			USA and Southern Canada	NAm
		Highly varying seasonal temperature	East Asia	EA
		Abundant precipitation throughout the year	New Zealand and Southeast Australia	SAu
			Southern parts of South America	SSAm
			South Africa	SAf
Warm/ Mediterranean	30°–45° N/S	Hot dry summer and mild wet winter	Southern Europe	SE
		Small annual temperature range	Western parts of North America (e.g. part of California)	WNAm
		Small annual precipitation		
Subtropical	10°–30° N/S	Seasonal changes between very wet, hot and a dry, cooler period	Eastern North America (e.g. Florida)	ENAm
			Central America	CAm
		High, tropical temperature during wet season	South and Southeast Asia	SAs and SEAs
		High precipitation during wet #season	Central and Southern Africa	CAf
			Northern Australia	NAus
Tropical	10°S–25°N	No significant seasonal changes in temperature and precipitation	Malay Archipelago (e.g. Indonesia, Singapore)	MAL
		High, tropical temperature throughout the year	Equatorial Africa (Congo basin)	EqAf
			Amazon basin	SAm
		High precipitation and humidity throughout the year		
Arid/desert	10°–30° N/S	Extremely dry and hot desert climate	North Africa (Sahara) and Arab	Saha
		Large diurnal variation of temperature	Central Australia	CAus
		Very small annual precipitation		

its potential was given mainly based on the productivity and growth rate of the plants in term of production rates and biomass yields per year. For each level of plants' growth rate, the evaluation is made according to Table 2.

Plant utilization options

According to this criterion, plants that possess high economical value and/or versatilities were better suited for the use in SFCWs so that the stakeholders can choose the most appropriate utilization option based on the demand for each harvesting season. Among the six utilization options are handicrafts (e.g. weaving materials, basketry, etc.), fertilizers (as composts), animal feeds, building and construction materials including insulation and thatching as well as fibre boards, paper making (due to high fibre and cellulose content in their stems), and pharmaceutical products. The evaluation of plant species is rated as followed.

Table 2 | Criteria rating for the versatility of utilization options as well as the growth rate of plant

Possible utilization options	Versatility	Growth rate of plant	Criteria rating
0 or 1 out of 6	Low	Low	0
2 out of 6	Moderately low	Moderately low	1
3 out of 6	Moderate	Moderate	2
4 out of 6	Moderately high	Moderately high	3
5 out of 6	High	High	4
6 out of 6	Very high	Very high	5

Nutrients uptake

It was reported that the uptake from most of the plants were only minor comparing to other removal mechanisms occurring in SFCWs, which is approximately 8% in term of nitrogen and 3% in term of phosphorus based on an average value calculated from several studies (Hurry & Bellinger 1990; Tanner 1994; Nyakang'o & van Bruggen 1999). As a result, this criterion is considered insignificance and is not needed to be considered for a recommendation table.

Treatment efficiency and tolerance to wastewater

The plants proposed in this study have been demonstrated that they are suitable for use in VSFCWs receiving municipal wastewaters. Nevertheless, direct organic removal in the form of BOD or COD by plant uptake is considered non-existence or can even be neglected (Kadlec *et al.* 2000). In term of the tolerance to wastewater, it can be stated that all the 45 plant species are suitable for the treatment of municipal wastewaters; however the exact ranges cannot be given for the most plants due to the wide research differences between the investigated case studies.

Cost of plants

The costs of purchasing the plant propagules, primarily seeds and seedlings, werebeen investigated. Price lists from several countries were analyzed and it was revealed that the cost differences between different species are marginal, and thus cannot be considered as a significant selection criteria. In order to support this argument, selected prices of wetland species from four companies in four different countries and continents are presented in Table 3.

The price is reported without any currency correction to make it simpler for the readers from each country to follow. Data from the table shows that cost differences between plant propagules are in most cases very marginal although some rare exceptions such as *Juncus effusus* in Australia might be also possible. It should be noted that apart from the selected price list, most of the collected data exhibit similar conclusions concerning the cost differences between the different wetland plants. Therefore, costs in this case should be of less concern than other criteria. Moreover, it is clear from this data that it is rarely to find the plants that available worldwide, let alone locally.

Presentation of the recommendation table

The idea behind recommendation table is to assist the decision makers while choosing the suitable plants during the planning phase. Based on 45 different plants under investigation, there were 13 species that scored at least 7 out of the maximum 10 points based along both versatility and productivity. The recommendation table of suitable alternative plants were proposed according to each climate zone. The results are shown in Table 4.

Table 3 | Prices of plant seeds from selected countries

Species	Generic name	USA* (US $)	Australia† (AUD $)	New Zealand‡ (NZD)	Germany§ (EUR)
Baumea articulata	Jointed twig-rush	–	6.00	1.80	–
Eleocharis sphacelata	Tall spike rush	–	5.50	2.0	–
Juncus effuses	Soft rush	1.05	6.50	1.8	2.20
Phragmites Australis	Common reed	–	5.50	–	2.00
Scirpus pungens	Olney's bulrush	1.05	5.50	–	–
Scirpus validus	Soft stem bulrush	–	5.50	1.6	–
Typha angustifolia	Narrow-leaved cattail	1.05	–	–	2.20
Typha latifolia	Broad-leaved cattail	1.05	–	–	2.20
Typha orientalis	Broad-leaved cumbungi	–	6.00	2.0	–

*Environmental Concern Inc., St. Michaels, Maryland, USA, 2008.
†Watergarden Paradise Aquatic Nursery, Sydney, NSW, Australia, 2008.
‡Koanga Gardens Ltd., Maungaturoto, New Zealand, 2005.
§Stauden Junge, Hameln, Germany, 2008.

Table 4 | Recommended alternative plant species in SFCWs according to each climate zone

Climate zone	Recommended Species	Generic name	Versatility rating	Productivity/ growth rate	Regions that are generally available
Cold	*Glyceria maxima*	Reed sweet grass	4	4	NE
	Phalaris arundinacea	Reed canary grass	4	3	NE
	Scirpus validus	Soft stem bulrush	3	4	NNAm
Temperate	*Glyceria maxima*	Reed sweet grass	4	3	CEE
	Miscanthus sacchariflorus	Amur silver grass	4	3	EAs
	Phalaris arundinacea	Reed canary grass	5	2	CEE
	Scirpus californicus	Giant bulrush	5	3	NAm, SSAm
	Scirpus lacustris	Common bulrush	3	4	CEE, SAf
	Scirpus validus	Soft stem bulrush	3	4	NAm, SAu
	Zizania latifolia	Manchurian wild rice	4	3	EAs
Warm	*Arundo donax*	Giant reed	5	4	SE
	Scirpus californicus	Giant bulrush	4	3	WNAm
Subtropical	*Arundo donax*	Giant reed	5	4	SAs
	Coix lacryma-jobi	Job's tear	4	3	CAm
	Miscanthus sacchariflorus	Amur silver grass	4	3	SEAs
	Pennisetum purpureum	Napier grass	5	3	SAs, SEAs
	Scirpus grossus	Greater club rush	4	4	SAs, SEAs
	Vetiveria zizanioides	Vetiver grass	5	5	SAs, SEAs, NAu
Tropical	*Cyperus papyrus*	Papyrus	5	4	EqAf
	Pennisetum purpureum	Kikuyu grass	5	3	SAm, SEAs
	Scirpus grossus	Greater club rush	4	4	MAY

No information could be found in the arid desert climate of North Africa (Sahara), Arab, and Central Australia; therefore this zone is omitted from the recommendation table. It can also be seen that there are several possibilities in each climate zone that the decision can be based on local availabilities as well as desired choices of utilization options. For example, one of the recommended plants presented in this study that possesses the highest score is Vetiver (*Vetiveria zizanioides*), which was found to be a potential plant for resource recovery in Southeast Asia as well as in Northern Australia. This species possesses very high versatility rating, and has already been demonstrated in the VSFCWs that the system can achieve the treatment performance comparable to the system planted with conventional wetland species (Kantawanichkul *et al.* 1999; Chomchalow & Chapman 2003). Hence, for the tropical climate it is highly recommended to apply this species in SFCWs.

CONCLUSION

It can be stated from the results that in most regions, there are more than one "most appropriate plant species," and as a result, it might not necessarily need to always use the conventional plants in SFCWs. To perform the selection, the operators should weight the results from each criterion according to their preference, and determine which plant will be used in the system. Productivity and economic versatility of macrophyte species can be a crucial decision and design factor for the choice of suitable plant species as differences in term of wastewater treatment efficiency are mostly not significant. To ensure that the resources will be recovered, significant efforts from every stakeholder are required as a part of good managerial measures. Several "how-to" practices and responsible stakeholders should be clearly specified and followed, for example who will decide how to utilize the plants after harvesting for each season, who will make use of them, and who will obtain the benefits from such practice.

REFERENCES

Chomchalow, N. & Chapman, K. 2003 Other uses and utilization of vetiver. Proceeding of the 3rd International Vetiver Conference, 6–9 October 2003, Guanzhou, China, 502–514.

Cooper, P. 2007 The constructed wetland association UK database of constructed wetland systems. *Water Sci. Technol.* **56**(3), 1–6.

Geiger, R. 1961 *Überarbeitete Neuausgabe von Geiger, R.: Köppen-Geiger/Klima der Erde (Revised new edition of climate of the earth)*. Scale 1:16 Million, Klett-Perthes Verlag, Gotha.

Heers, M. 2006 *Constructed wetlands under different geographic conditions: evaluation of the suitability and criteria for the choice of plants including productive species*. Master Thesis, Faculty of Life Sciences, Hamburg University of Applied Sciences, Hamburg, Germany.

Hurry, R. J. & Bellinger, E. G. 1990 Potential yield and nutrient removal by harvesting of *Phalaris arundinacea* in a wetland treatment system. In: Cooper, P. F. & Findlater, B. C. (eds) *Constructed Wetlands in Water Pollution Control*. Pergamon Press, Oxford, pp. 543–546.

Kadlec, R. H. & Knight, R. L. 1996 *Treatment Wetlands*. CRC Press, Lewis Publishers, Boca Raton, Florida.

Kadlec, R. H., Knight, R. L., Vymazal, J., Brix, H., Cooper, P. F. & Haberl, R. 2000 *Constructed wetlands for pollution control: processes, performances, design and operation*. Scientific and technical report series No. 8, IWA Publishing, London.

Kantawanichkul, S., Pilaila, S., Tanapiyawanich, W., Tikampornpittaya, W. & Kamkrua, S. 1999 Wastewater treatment by tropical plants in vertical-flow constructed wetlands. *Water Sci. Technol.* **40**(3), 173–178.

Nyakang'o, J. B. & van Bruggen, J. J. A. 1999 Combination of a well functioning constructed wetland with a pleasing landscape design in Nairobi, Kenya. *Water Sci. Technol.* **40**(3), 249–256.

Reed, S. C., Crites, R. W. & Middlebrooks, E. J. 1995 *Natural Systems for Waste Management and Treatment*, 2nd edition. McGraw-Hill Inc, New York.

Tanner, C. C. 1994 Growth and nutrition of *Schoenoplectus validus* in agricultural wastewaters. *Aquatic Botany* **47**(2), 131–153.

Vymazal, J. 1996 Constructed wetlands for wastewater treatment in the Czech Republic the first 5 years experience. *Water Sci. Technol.* **34**(11), 159–164.

Wissing, F. & Hoffmann, K. F. 2002 *Wasserreinigung mit Pflanzen (Water treatment with plants)*, 2nd edition. Verlag Eugen Ulmer, Stuttgart.