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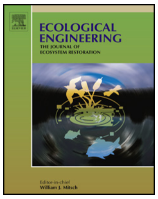

Emergent plants used in free water surface constructed wetlands: A review

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ABSTRACT

Constructed wetlands with free water surface (FWS CWs) have been used for many purposes worldwide. Emergent macrophytes play important roles in FWS CWs; they reduce wind speed and thus support sedimentation and prevent re-suspension, provide substrate for periphyton and bacteria, take up nutrients and in carbon-limited systems provide carbon for denitrification during biomass decomposition. It has been reported that treatment performance of planted FWS CWs is superior to unvegetated lagoons. However, treatment performance of FWS CWs could be affected by plant species used. The literature survey of 643 FWS CWs from 43 countries recorded 150 plant species and revealed that the most commonly used macrophyte genera were *Typha*, *Scirpus* (*Schoenoplectus*), *Phragmites*, *Juncus* and *Eleocharis.* In terms of species, most frequently used species were *Typha latifolia*, *Phragmites australis*, *Typha angustifolia*, *Juncus effusus*, *Scirpus lacustris*, *Scirpus californicus* and *Phalaris arundinacea.* In terms of continents, *P. australis* is the most frequent species in Europe and Asia, *T. latifolia* in North America, *Cyperus papyrus* in Africa, *P. australis* and *Typha domingensis* in Central/South Americas and *Scirpus validus* (*S. tabernaemontani*) in Oceania.

1. Introduction

A typical free water surface constructed wetland (FWS CW) with emergent macrophytes is a shallow basin containing 20–30 cm of rooting soil, with a water depth of 20–40 cm. There are no specific requirements for soil quality: the major role of soil is to support plant growth. As wastewater flows through the wetland, it is treated by sedimentation, filtration, oxidation, reduction, adsorption and precipitation processes (Kadlec and Wallace, 2009).

FWS constructed wetlands are commonly used for treatment of runoff waters such as urban (Scholes et al., 1999; Davies et al., 2001), road and highway (Pontier et al., 2004), airport (Thorén et al., 2003), golfcourse (Kohler et al., 2004), agriculture (Raisin et al., 1997; Jordan et al., 1999; Anconelli et al., 2007; Maniquiz et al., 2012). FWS CWs have also extensively been used for treatment of drainage waters from coal mines (Wieder, 1989; Sobolewski, 1996; Goulet and Pick, 2001), metal ore mines (Lan et al., 1990; Overall and Parry, 2004) or pastures (Raisin and Mitchell, 1994; Tanner et al., 2005). Also, FWS CWs are used for treatment of concentrated agricultural wastewaters from swine (e.g., Poach et al., 2007), dairy (Morioka et al., 2006; Gottschall et al., 2007) or farmyard (Dunne et al., 2005) operations. In many countries, FWS CWs are used to treat municipal sewage (Greenway and Woolley, 1999; Mander et al., 2001; Cameron et al., 2003; Brix et al., 2011). FWS CWs also have been used for treatment of other types wastewater such as landfill leachate, woodwaste leachate, refinery process waters, pulp and paper effluents, fish hatcheries, abattoir or sugar factory (Vymazal and Kröpfelová, 2008; Vymazal, 2011a).

The presence of macrophytes is one of the most conspicuous features of constructed wetlands and their presence distinguishes them from unplanted soil filters or lagoons. The macrophytes growing in constructed wetlands have several properties related to the treatment process that make them an essential component of the design (Brix, 1994, 1997). The most important effects of emergent macrophytes in wastewater treatment in free water surface CWs are (1) the physical effects of the plant tissue, e.g. reduction of wind speed which supports sedimentation of suspended solids, prevents re-suspension (Pettecrew and Kalff, 1992; Sommer et al., 1996), filtration effect (Cronk, 1996) or provision of surface for attached microorganisms (Chappell and Goulder, 1994) and (2) plant metabolism such as plant uptake and oxygen release from roots (Brix, 1994). Plant uptake could be significant route for nutrient removal, especially under low loading rates (Gottschall et al., 2007). However, the release of oxygen plays a lesser role in FWS CWs as most treatment processes occur in the water column and within the litter layer on the bottom. Decaying plant biomass may also provide organic carbon necessary for denitrification.

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Several authors pointed out that there could be a difference in treatment efficiency in relation to plant species. Bachand and Horne (2000) found much higher removal of nitrogen in a *Typha* sp. wetland (565 mg N m^{-2} d^{-1}) compared to a *Scirpus* sp. wetland (261 mg N m^{-2} d^{-1}) in California. Bojcevska and Tonderski (2007) reported higher mass removal of ammonia-N in a wetland planted with Papyrus (*Cyperus papyrus*) compared to Antelope grass (*Echinochloa pyramidalis*) in a constructed wetland treating effluent from sugar factory stabilization pond in Kenya, however removal of TSS and TP was not affected by plant species. In the experiments carried out in mesocosm FWS CWs mesocosms in Thailand, Klomjek and Nitisoravut (2005) found that units with Asia crabgrass (*Digitaria bicornis*) removed more BOD_5 and TSS than units planted with Cattail (*Typha angustifolia*). Lin et al. (2002) compared the ability of five macrophytes – Common reed (*Phragmites australis*), Napier grass (*Pennisetum purpureum*), Water spinach (*Ipomoea aquatica*), Water lettuce (*Pistia stratiotes*) and Asiatic dayflower (*Commelina communis*) to support denitrification through release of organic carbon under experimental conditions in Taiwan. The results revealed that FWS units with *Pennisetum* provided consistently higher nitrate removal that FWS units planted with other species.

Yang et al. (2007) compared the ability of five macrophyte species, *P. australis, Typha latifolia*, *Canna indica* (Canna) *Vetiveria zizanoides* (Vetiver) and *P. purpureum* to remove contaminants in mesocosm FWS CWs mesocosms in Guangzhou in south China. The authors reported that units vegetated with *P. purpureum* significantly outperformed units with other species in May/June while mesocosms with *P. australis* and *C. indica* were more efficient during the period August–December. All vegetated wetlands exhibited more efficient removal of TP and TN than unvegetated units but there was no difference in removing organics. Elsaesser et al. (2011) found that constructed wetlands planted with *Phalaris arundinacea* and *T. latifolia* reduced substantially more concentrations of pesticides than unvegetated filters in the FWS CWS in Norway. Uptake of plants was low but higher for cells vegetated by *P. arundinacea* than for cells vegetated by *T. latifolia*.

The density of vegetation affect detention time in the FWS constructed wetlands – the detention time increase with plant density (Jaddhav and Buchberger, 1995). Various plants differ in “porosity” – Cronk (1996) reported decreasing porosity in the order of *Phragmites* (98%) > *Typha*, *Juncus* (95%) > *Scirpus* (86%). Porosity is the ratio of water volume to the volume of the water body including plants. The higher porosity, the lower volume of plant parts submerged in the water and subsequently lower area for attached periphyton and lower filtration effect. Hill and Payton (2000) measured the effect of plant density on water temperature in a FWS CW at the Auburn University, Alabama. Unvegetated cells had significantly higher temperature than cells with Duck potato (*Sagittaria lancifolia*), *P. australis* and *Scirpus* spp. and also exhibited greater daily variation in temperature than vegetated cells. The more densely vegetated cells had significantly higher water temperature during winter period.

The objective of this paper is to evaluate the use of various plant species in free water surface constructed wetlands designed for wastewater treatment. The information from 643 constructed wetlands in 43 countries reported in the literature was evaluated.

2. Survey results

In Table 1, examples of emergent macrophytes used for FWS CWs designed for treatment of various types of wastewater in 43 countries worldwide are presented. FWS constructed wetlands have been used extensively in many countries, particularly in Australia, Canada, Korea, Sweden, Taiwan, Thailand, United Kingdom and first of all, in the United States.

The literature survey of 643 FWS CWs identified as many as 150 macrophyte species used worldwide. In Table 3, five most frequently used genera are shown with *Typha* spp. being the most common. The survey also revealed that most FWS CWs, contrary to subsurface flow CWs (Vymazal, 2011b), are very often planted with several species (Table 1). There is no clean pattern in the use of certain species for a certain type wastewater with the exception of the use of cattails (*Typha* spp.) for treatment of acid mine drainage (e.g., Wieder, 1989).

2.1. Most common species used in FWS CWs

2.1.1. Typha spp.

Typha spp. (Cattails, Typhaceae) are erect rhizomatous perennial plants with jointless stems. The plants are up to 4 m tall with an extensive branching horizontal rhizome system. Leaves are flat or slightly rounded on the back, in their basal parts spongy (Sainty and Jacobs, 2003). Most *Typha* species prefer soils rich in organic matter. Cattails prefer standing waters, however, various species of *Typha* prefer different water depth and water depth fluctuation. Cattails very often invade natural wetlands and displace native species. Also, when planted in constructed wetlands, they tend to out-compete other species planted in the wetland. The most frequently used species in FWS CWs is *T. latifolia* L. (Common cattail, Broad-leaved cattail) which has been reported within the survey in 320 CWs from all continents except Central and South America (Table 2). *T. angustifolia* L. (Narrow-leaved cattail) is the second most frequently used cattail in FWS CWs. It has been reported from 65 FWS CWs worldwide with the exception of Africa and Oceania. *Typha domingensis* Pers. (Southern cattail, Santo Domingo cattail) and *Typha orientalis* C. Presl (Broadleaf cumbungi, Raupo) are the cattail species commonly used in FWS CWs in Oceania. Also, *T. domingensis* is the dominant macrophytic species in the Everglades Stromwater Treatment Areas (Dierberg and DeBusk, 2008). Other *Typha* species used in FWS CWs is *Typha angustata* L. (Lesser cattail) which was used in Asia.

2.1.2. Scirpus (Schoenoplectus) spp.

Species belonging to the genus *Scirpus* (Bulrush, Cyperaceae) are annual or perennial herbs which grow in tufts or large colonies. Stems are sharply triangular or slightly rounded and softly angled, up to 3 m tall or even taller in some species. Roots penetrate down to 70–80 cm resulting in greater root-zone aeration and. However, in constructed wetlands *Scirpus validus* roots penetrate sometimes only to 10–30 cm (Tanner, 1994; Pullin and Hammer, 1991).

Scirpus lacustris L. (syn. *Schoenoplectus lacustris* (L.) Palla) (Common clubrush) was used by Seidel at early stages of the development of constructed wetlands for wastewater treatment (e.g., Seidel, 1965, 1976) and it is still used in Europe (Table 2). Other *Scirpus* (*Schoenoplectus*) species are mostly used in North America, Australia and New Zealand (Table 2) (e.g., Tanner, 1994; Behrends et al., 1994; Wallace and Knight, 2006; Kadlec and Wallace, 2009). In Australia and New Zealand, *S. validus* Vahl. (River clubrush, syn. *Schoenoplectus validus* (Vahl.) A. Löwe and D. Löwe) has been predominantly used. The species is now often called *Scirpus* (*Schoenoplectus*) *tabernaemontani* in this region.

In North America, various *Scirpus* (*Schoenoplectus*) species have been reported 174 times (Table 3). The most frequently used species were *Scirpus acutus* Muhl. ex. Bigel. (Hardstem bulrush, syn. *Schoenoplectus acutus* (Muhl. Ex Bigelow) A. Löwe and D. Löwe var. *acutus*), *Scirpus americanus* (Pers.) Volkart ex Schinz & R. Keller (Chairmaker’s bulrush), *Scirpus californicus* (C.A. Meyer)