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# A novel biofilm carrier for pollutant removal in a constructed wetland based on waste rubber tire chips

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## ABSTRACT

The increasing number of waste tires has posed a serious threat to environmental protection and public health efforts in recent years. Waste rubber tire chips (WRTCs) are introduced as a novel media and biofilm carrier of subsurface flow (SSF) constructed wetland (CW), which is combined with free water surface (FWS) CW to form a hybrid experimental system. Two parallel hybrid CW systems are used: a control CW system uses a SSF CW with a gravel bed while WRTC is the SSF media for the other hybrid CW system. Comparing the experimental results of hybrid CWs with those of WRTC bed and gravel bed reveals that withered vegetation does not significantly influence the biochemical oxygen demand (BOD) removal performances for individual CWs or hybrid CW systems. However, withered vegetation deteriorates the removal performance of ammonia-nitrogen ($NH_3$-N). Regrowing vegetation restores the CW ability of gravel SSF CW to remove $NH_3$-N. The original vegetation of WRTC SSF CW, reeds, is dead in the winter. Some new superior vegetations, barnyard grass and globose bead hat-sedge make a removal performance comparable to that of gravel bed SSF CW. Owing to some steel belts connected to WRTC, iron ions are naturally released into the SSF CW and increase nitrate average removal rates of gravel bed SSF CW, −13.1%, to that of WRTC bed SSF CW, 62.2%. The hybrid CW with WRTC SSF CW is nearly twice the nitrate removal rate of the hybrid CW system with gravel SSF CW. As for total phosphorus (TP) removal performance, the average removal rates are 10.0% and 39.9% for gravel SSF CW and WRTC SSF CW, respectively. Moreover, the TP average removal rate of WRTC hybrid CW, 53.4%, is superior to that of gravel hybrid CW, 27.2%.

## 1. Introduction

The global production of tires is approximately 1.4 billion units which correspond to an estimated 17 million tons of used tires annually. The widely differing chemical compositions and the cross-linked structures of rubber in these tires largely account for its high resistance to biodegradation, photochemical decomposition, chemical reagents and high temperatures. The increasing numbers of waste tires thus poses a serious environmental threat (Sienkiewicz et al., 2012). The extent to which these used tires pose an environmental and public health generally increases when they are dumped as evidenced by the estimated 4 billion used tires in landfills and stockpiles worldwide (WBCSD, 2008). In particular, those dumps pose threats in the form of potential fires and a breeding ground for rodents, snakes, as well as disease-carrying mosquitoes (Barbooti et al., 2004; Li et al., 2006; Tang et al., 2006). To prevent the further spread of pollution and disease, most industrialized countries worldwide prohibit the stockpiling of waste tires in landfills. Some substitution policies are also enacted, including retreading, energy recovery, pyrolysis, product recycling, and material recycling (i.e. grinding and devulcanization). The recovery rate exceeded 84% for Europe, Japan and the United States in 2006 (RMA, 2009; ETRMA, 2011; JATMA, 2012). Based on the obtained data of ETRMA (2011), most used tires are treated through energy recovery and material recovery, whose percentages are 48% and 36%, respectively. As increasing oil prices have led to the search for alternative energy sources in order to ensure sustainable economic growth, waste tires are used as an alternative fuel source, mainly for use in cement kilns, paper/pulp mills, thermal power stations, and industrial boilers. Waste tires can also replace coal for use in steel plants (Pipilikaki et al., 2005; Conesa et al., 2008; Singh et al., 2009). Pyrolysis decomposes waste tires into gas, pyrolysis oil

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and char, all of which are high calorific products capable of use as an alternative fuel (Fernandez et al., 2012). Converting waste tires into alternative fuels requires complying with technical and financial support-related requirements, which also limit its applications. Other usages of waste tires with a lower cost can be found in material recovery. Some successful applications of whole or shredded tires are found in various civil engineering projects, including embankments, backfill for walls, road insulation, field drains, erosion control/rainwater runoff barriers, crash barriers, jetty bumpers, and rubber-modified asphalt (ETRMA, 2011). In addition to energy recovery, devising a more feasible means of treating waste tires with lower technical and financial constrains is an important environmental issue worldwide.

If global water consumption patterns continue without an immediate solution, two out of three individuals worldwide may be living in a water-stressed condition by 2025 (UNEP, 2000). Based on a strategy of creating more water resources, water recovery is a viable means of offering more qualified water for specific usages. As is forecasted global demand for recycled water will increases by 181% from 2005 to 2015 (Tanik, 2010) necessitating the adoption of low impact development techniques and implementation of sustainable infrastructure such as constructed wetlands and waste utilization. CW with water-tolerant plants and gravel or soil can remove various pollutants from wastewater by microbial, physical and chemical mechanisms (Hamilton et al., 1997; Reed, 2000; García et al., 2004; Voeks and Rahmatian, 2004). Two wetland treatment systems include surface flow constructed wetland and subsurface flow constructed wetland. In these constructed wetland, a bed of gravel or soil functions as a substrate for growth of rooted wetland plants (Kadlec and Wallace, 2008). Three categories of SSF substrate are usually used: natural products, man-made products, and industrial by-products (Vohla et al., 2011). Considering the prices and sources, gravels or sands are undoubtedly the most popular natural substrates (Tanner et al., 1999; Pant et al., 2001; Vohla et al., 2005; Albuquerque et al., 2009; Li et al., 2010; Allende et al., 2012). Other alternatives of SSF substrates include peat, limerock, shale, zeolite, wollastonite, marble, vermiculite, anthracite, laterite, bauxite, maerl, shells and, calcite, glauconite, apatite, dolomite, granite and sepiolite (Wood and McAtamney, 1996; Drizo et al., 1999; Gray et al., 2000; Hill et al., 2000; Roseth, 2000; Brix et al., 2001; Arias et al., 2003; Molle et al., 2005; Vohla et al., 2005; Prochaska and Zouboulis, 2006; Chazarenc et al., 2007; Dordio et al., 2009; Wu et al., 2011; Allende et al., 2012). Some man-made products used in SSF include lightweight aggregates, filtralite P™, filtralite NR, norlite, granular activated carbon, Filtra P, light expanded clay aggregates and ceramic filter media (Drizo et al., 1999; Hill et al., 2000; Scholz and Xu, 2002; Gustafsson et al., 2008; Albuquerque et al., 2009; Dordio et al., 2009; Koiv et al., 2009; Li et al., 2010).

In addition to the previous substrates, industrial by-products are promising alternatives for SSF. Such by-products are a solution not only for solid waste, but also for wastewater treatment. Environment related studies have focused on decreasing treatment costs of solid waste disposal and wastewater treatment. Other studies have demonstrated that slag, oil shale ash, oyster shell, burnt oil shale, ochre and coal fly ashes are highly promising for use in pollutant removal (Drizo et al., 1999; Heal et al., 2005; Seo et al., 2005; Vohla et al., 2005; Chazarenc et al., 2007; He et al., 2007; Li et al., 2010). Graf and Xie (2000) and Tang et al. (2006) used crumb rubber is used as an alternative media for filtration of wastewater treatment achieving a significant reduction in the removal of turbidity, particles, phytoplankton and zooplankton. In contrast to conventionally adopted granular media filters, crumb rubber filters using this media require fewer backwashes and lower head loss is incurred as well. Those studies also suggested the potential use of crumb rubber filtration as a primary treatment technology increases the efficiency of a secondary treatment process. Above studies further demonstrate the highly promising potential of waste rubber tires in wastewater treatment.

Despite the above developments, to our knowledge, the feasibility of using waste rubber tire chips as a media in SSF CW has never been examined. Therefore, this study investigates a wider application of waste rubber tires in wastewater treatment. Based on the removal of organic pollutants and nutrients, two parallel hybrid CW systems, whose substrates in SSF are gravel and WRTC, are compared to investigate the substitution of WRTC for traditional substrates. In addition to offering a wider source of SSF substrate for lower construction cost, results of this study demonstrate an innovative connection between solid waste treatment and water resource recreation.

## 2. Materials and methods

### 2.1. Setup of experimental CW models

Some hybrid constructed wetland systems are developed for a more stable removal rate of pollutants. Related studies indicate that hybrid constructed wetlands can effectively remove organic matter, suspended solids and nutrients (Shi et al., 2004; Abidi et al., 2009; El-Khateeb et al., 2009). Due to a more stable performance in pollution treatment, hybrid constructed wetlands are highly promising constructed wetland systems. By considering a clog problem induced by suspended solid and environmental constraints of nitrification and denitrification, hybrid constructed wetland systems are combined with FWS and SSF CW in a series. Two laboratory scale CW systems (i.e. system G with gravel bed SSF CW and system W with WRTC bed SSF CW) are installed as Fig. 1. Reaction tank dimensions of CW are 2.0 m in length, 0.6 m in width and 0.5 m in height. A design water depth is 30 cm for all CW systems. In FWS CW of both system G and system W, the thickness of bottom soil to plant with emergent macrophytes have about 15 cm of soils. The macrophytes in Taiwan, Cattail (*Typha orientalis* Presl.) and reed (*Phragmites communis* L.), are superior to other local aquatic plants in wastewater treatment (Jin et al., 1997; Wang et al., 1999). The former is planted in FWS CW of both systems while the latter is used as aquatic plants for both SSF CW systems. As winter approaches, the reeds in both SSF CW systems wither and only the reeds in system G regrow. Notably, the reed does not grow well even when replanting new reeds. Four months later, barnyard grass (*Echinochloa crus-galli* (L.) P. Beauv.) and globose bead hat-sedge (*Cyperus difformis* L.) become superior species during the remaining operational period. These plants are regarded as new aquatic plants for

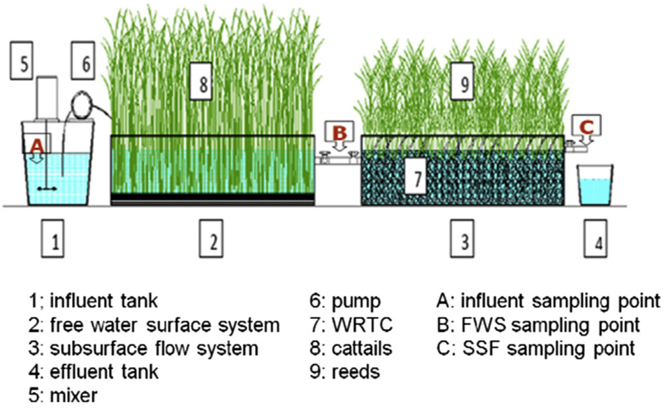

**Fig. 1.** Laboratory setup of constructed wetland systems.