Recent developments in wetland technology for wastewater treatment

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An Xing
Supervisor: Stefan Weisner
**Abstract**

Constructed wetlands for wastewater treatment have substantially developed in the last decades. As an eco-friendly treatment process, constructed wetlands may enable the effective, economical, and ecological treatment of agricultural, industrial, and municipal wastewater. The present study reviews the recent developments in wetland technology for wastewater treatment from articles published from 2011 to 2012. The papers were searched from Web of Science using the key words constructed wetland and wastewater treatment. Up to 32 articles were selected and a table describes the recent enhancements in wetland treatment technology. Some articles presented notable results, with higher pollutant removal rates or related to some important factors in removal processes. These articles were separated into three main parts, namely, enhancement of nitrogen removal, phosphorus removal and recovery, and wetland contribution to heavy metal removal. The recent trends in the enhancement of wetland treatment were identified. The major enhancement methods for nitrogen, BOD, and COD reduction are hybrid water flow wetland designs and the combination of porous substrates with conventional gravel. Organic substrates, such as wood mulch and rice husk, are a suitable option for the upper porous media. The recent promotion of phosphorus removal involves a solution to internal loading and an inexpensive substrate source. Fragmented Moleanos limestone and alum sludge cake from the water plants present the feasibility of P removal. The main improvement in heavy metal removal depends on the substrate and combination of different treatment methods. Additionally, the free water surface constructed wetland was proven as a stable heavy metal treatment method. Vegetation was confirmed to enhance the removal rate of all wetland types for all kinds of pollutants. However, the species of the vegetation does not significantly influence the removal rates.

*Key words:* constructed wetland, wastewater treatment, nitrification, denitrification, phosphorus removal, heavy metals removal, review
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1 Introduction

 Constructed wetlands (CWs), as a method for wastewater treatment, have developed rapidly in the past two decades (Kadlec, 2008). Compared with conventional wastewater treatment, CWs are a low-cost alternative in terms of construction, operation, and maintenance. Considering the development of treatment wetlands, CWs have become a reasonable option for treating livestock wastewater, farmland leaching water, landfill leachate, and domestic sewage (Lu, 2011). The interaction and application of constructed wetland technology offers more selections and combinations for wastewater treatment systems (Kadlec, 2008).

 CW wastewater treatment systems have three patterns of water flow: free water surface (FWS), horizontal subsurface flow (HSSF), and vertical flow (VF) wetlands (Kadlec, 2008). FWS wetlands require little cost during construction and are easy to manage. However, large areas of wetland are required for FWS wetlands to treat wastewater. Therefore, open water areas cause pathogen problems. Commonly, FWS wetlands are ideal breeding fields for mosquitoes and bacteria during summertime. Another drawback of FWS wetlands is limited water flow and decreased retention of pollutants when their surface freezes during winter (Li et al., 2012). HSSF and VF wetlands are highly efficient in pollutants removal and require less area than FWS wetlands. Research results show that HSSF and VF wetlands perform well in treating heavy metals and trace elements. The disadvantages of these two kinds of wetlands are clogging and high cost. Clogging of subsurface flow wetlands may reduce their lifespan by one-tenth (Nivala et al., 2012).

 Several pollutants are removed by CWs. Biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, phosphorus, trace elements, and some metals like aluminium, copper, mercury, and zinc are common pollutants, which are treated using CWs (Kadlec, 2008). Among these pollutants, N and P, which commonly occur in agriculture, industrial wastewater, domestic sewage, landfill leachate, and storm water, are the main targets of wetland treatment. N occurs in different states in wetland biogeochemical cycles, such as nitrate (NO$_3^-$) and ammonium (NH$_4^+$-N). The N removal in CWs is based on ammonification, nitrification, and denitrification, plant uptake, and microbial assimilation, as well as ammonia volatilization, filtration, and adsorption (Kadlec, 2008). Phosphorus, as another factor in eutrophication, usually limits the growth of plants and algae in inland waters. Phosphorus removal in wetlands occurs by storing in the sediment and soil via the sedimentation of particulate P, chemical precipitation and adsorption of soluble P, and deposition of suspended organic matter (Kadlec, 2008).

 Due to the increasing use of treatment wetlands in the last decade, improving wetland
technology for wastewater treatment is necessary and urgent. The object of this thesis is to obtain a picture of the research achievements on wetland technology for wastewater treatment published from January 2011 to April 2012 by searching, summarizing and contrasting relevant papers.

2 Methods

The present study is based on various studies published from January 2011 to April 2012 that focus on CW treatment function. The articles were searched from the Web of Science using the key words constructed wetland and wastewater treatment. From January 2011 to April 2012, more than 250 articles matched the key words. The selection aims to find studies related to recent developments in the enhancement of treatment wetland technology. The principles of paper selection were as follows:

Inclusion criteria
1. The article should be related to the enhancement of treatment wetlands or important factors in wetland construction, especially studies focusing on N, P, and metal removal.
2. The articles involve in financial analysis or governmental decisions were excluded.

Exclusion criteria
1. The article should be available in full version.
2. The article should not be a review.
3. The papers relating to evaluations of common CWs in treating some kinds of special wastewater or the treatment efficiencies of CWs in different weathers were excluded.

A total of 32 articles were selected.

The present study has two main parts. The first part is an overview of the 32 papers, which is divided based on the major pollutants and main factors in the removal processes investigated in each study, namely N, P, heavy metals, BOD, COD, and other factors. Each of the groups is characterized in a table with descriptions, wetland flow type, and references.

Nine of the studies have higher significance, demonstrating higher removal rates or the relationship of important factors in removal processes. The second part discusses the studies in detail, which are marked with bold in the tables. Comments regarding the study were concluded following each detail description. Finally, the overall trend is discussed in the discussion.

3 Overview of 32 articles

3.1 Nitrogen removal
Table 1 lists the articles that mainly involve N removal. The wetlands in the investigations about N removal include conventional types, namely, horizontal subsurface flow, free water surface, and vertical subsurface flow CWs, as well as novel types such as tidal flow CWs, baffled flow CWs, hybrid CWs, and subsurface wastewater infiltration systems.

The most common object of the investigations is the capacity of novel substrates. Tee et al. (2011) investigated the feasibility of rice husk-gravel mixed substrate in a new baffled HSSF CW. The roots of vegetation are able to grow deep in rice husks, which provide high uptake and nitrification.

Bialowiec et al. (2011) proved that lightweight aggregates made from the fly ash from sewage sludge thermal treatment (FASSTT LWA) is better than the conventional gravel substrate in VF CW for N treatment. They found that 25 cm upper FASSTT LWA and 75 cm lower gravel layer is the optimal N treatment combination.

Saeed et al. (2011a) confirmed that organic substrates such as wood mulch and gravel–wood mulch are efficient in VF CWs but not in HSSF CWs. A subsequent investigation tested the removal capacities of a wood mulch VF-gravel HSSF-zeolite VF system (Saeed et al. 2011b). The wetlands present high nitrification during operation, and both wood mulch and zeolite were more efficient than gravel (Saeed et al. 2011b).

Another important issue is the capacity of novel hybrid wetlands. A complex wetland consists of one or more HSSF wetlands and VF wetlands or a combination of horizontal and vertical flowing situation. Tee et al. (2011) designed a new baffled HSSF CW wherein VF occupies a small area. The study confirmed that complex wetlands provide the advantages of both HSSF and VF CWs and they are efficient for N treatment.

Some studies tested wet–dry cycling, which is a new method for introducing oxygen into the substrate. In tidal flow CWs, wastewater is not fed continuously, but is controlled by a flood–drain cycle. During the cycle, oxygen is enters the substrate during the drain period, thereby providing oxygen for nitrification (Wu et al. 2011).

Additionally, Hu et al. (2011) investigated the application of tidal flow CW in livestock wastewater treatment. The investigation confirmed the efficiency of tidal flow CWs in treating wastewater from a variety of livestock. Disinfectants UNIPRED and HYPROCLORED decreased and inhibited the microbial activities.

Li et al. (2011a) confirmed the capacity of a constructed subsurface infiltration system (CSWIS). The investigation regarding shunt distribution and intermittent operation mode tested a new hydraulic controlling system for N and BOD treatment (Li et al.
These two studies provide a reasonable strategy for domestic sewage treatment.

Table 1. Papers that focused on nitrogen. Studies in bold font are described with more detail in subsequent sections.

<table>
<thead>
<tr>
<th>Description of study</th>
<th>Type of wetland</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>The study proved that lightweight aggregates made from the fly ash from sewage sludge thermal treatment is better than simple gravel as a substrate for ammonia, nitrate, and nitrite removal.</td>
<td>Vertical flow CW</td>
<td>Bialowiec et al. (2011)</td>
</tr>
<tr>
<td>Tested the biogeochemical characteristics of the sediment in 2 cells (one was next to the inlet and another one was next to the outlet) of a FWS CW. The chemical analysis is focused on N and P.</td>
<td>FWS CW</td>
<td>Erler et al. (2011)</td>
</tr>
<tr>
<td>Investigated the changes in nitrogen removal after adding disinfectant to livestock wastewater in a CW.</td>
<td>Tidal flow CW</td>
<td>Hu et al. (2011)</td>
</tr>
<tr>
<td>Evaluated the shunting distribution of sewage and intermittent operation mode in constructed subsurface infiltration system</td>
<td>Constructed subsurface infiltration system</td>
<td>Li et al. (2011a)</td>
</tr>
<tr>
<td>An investigation of the nitrogen removal rate of a subsurface wastewater infiltration system with an effective depth of 1.5 m and a fluctuant hydraulic loading rate</td>
<td>CSWIS</td>
<td>Li et al. (2011b)</td>
</tr>
<tr>
<td>A simulation of nitrogen species using the advection–dispersion–reaction equation with linear sink-source terms</td>
<td>HSSF CW</td>
<td>Moutsopoulos et al. (2011)</td>
</tr>
<tr>
<td>A comparative evaluation of the pollutant removal efficiencies of different substrates (i.e. gravel, organic wood mulch, and gravel–wood mulch)</td>
<td>VF CW, HSSF CW</td>
<td>Saeed et al. (2011a)</td>
</tr>
<tr>
<td>A comparative experiment between alternative substrate (wood mulch, zeolite) and gravel for nitrogen treatment in a VF-HF-VF hybrid CW</td>
<td>Hybrid CW</td>
<td>Saeed et al. (2011b)</td>
</tr>
<tr>
<td>Tested the relationship between plants physiologic parameters and nitrogen concentration in CW</td>
<td>Horizontal subsurface CW</td>
<td>Shelef et al. (2011)</td>
</tr>
<tr>
<td>Investigated the capacity of baffled subsurface-flow CW with a rice husk–gravel substrate</td>
<td>Baffled subsurface-flow CW</td>
<td>Tee et al. (2012)</td>
</tr>
<tr>
<td>Investigated the oxygen transfer capacity and microbial contaminant removal processes in a laboratory-scale tidal flow CW</td>
<td>Tidal flow CW</td>
<td>Wu et al. (2011)</td>
</tr>
</tbody>
</table>
3.2 Phosphorus removal

Table 2 shows the studies involving P removal and recovery, most of which tested the substrate. These include determining the capacity of a novel substrate, estimating the internal loading of sediment, assessing the water plant by-product with alum sludge as the substrate in the treatment CW, and the recovery of P from the alum sludge substrate.

A recovery concept was presented by Zhao et al. (2011a), which investigated the capacity of alum sludge from drinking water treatment plants as a substrate for HSSF treatment wetlands. They also investigated the feasibility of P recovery from the alum sludge substrate (Zhao et al. 2011b). These two investigations provide a sustainable treatment system.

Palmer-Felgate et al. (2011) investigated the measurement of internal loading in the sediment of FWS CW using diffusive equilibrium in thin films and equilibrium P concentration and they determined that the two methods decrease the SRP flux. The result demonstrates that macrophytes play an important role in preventing the release of SRP from the sediments. By contrast, the dredging of reed beds has no significant influence on SRP release.

Bruch et al. (2011) investigated the P treatment efficiency of three different substrates, lava sand, conventional fluviatile sands, and zeolite mixed with lava sands, in VF CW. According to the experiments, the adsorption capacity of lava sand is not significantly higher than that of conventional fluviatile sands. The tests also confirmed that zeolite increases the sorption ability. Zeolite promotes the hydraulic retention time by increasing the shrinkage and swelling capacity.

Lindstrom et al. (2011) investigated four methods for reducing P internal flow, namely soil dry down, surface addition of alum carbonate, surface addition of calcium carbonate, physical removal of the accreted organic soil under both aerobic and anaerobic water column conditions. The results show that soil dry down and surface alum addition efficiently reduce P internal flow, whereas the other two methods are not as effective. Based on the earlier investigations, the maximum alum-based P removal only occurs during the first few months. Therefore, organic soil removal is the reasonable method for reducing the P flux from the soil and decreasing internal P loading.

**Table 2.** Papers that mainly focused on phosphorus. Studies in bold font are described with more detail in subsequent sections.

<table>
<thead>
<tr>
<th>Description of study</th>
<th>Type of wetland</th>
<th>Reference</th>
</tr>
</thead>
</table>

5
Comparison between lava sand and conventional fluviatile sands in municipal wastewater treatment

Tested four methods for reducing internal soluble reactive P flow in a free water surface flow treatment CW, namely, soil dry down, surface addition of alum carbonate, surface addition of calcium carbonate, physical removal of the accreted organic soil under both aerobic and anaerobic water column conditions

**Tested the capacity of FML as substrate in P treatment**

HSSF CW Mateus et al. (2011)

Comparison between the DET and the EPC0 method for measuring the soluble reactive P released from the sediment in an FWS CW

FWS CW Palmer-Felgate et al. (2011)

**Assessment of alum sludge-based CW treatment ability and the use of water plant by-product alum sludge as a substrate for treatment CW**

Mesocosm field-scale HSSF CW Zhao et al. (2011a)

**Determined the feasibility of using recovered aluminium sludge substrate as a potential P and Al resource**

Zhao et al. (2011b)

### 3.3 Heavy metal removal

Table 3 includes the papers related to heavy metal removal. Allende et al. (2012) tested gravel, coco-peat, zeolite, and limestone as substrates for VF CWs in treating metals, such as arsenic, boron, and iron. At an average hydraulic loading of 0.073 m$^3$/(m$^2$d), limestone exhibited the highest removal rate for arsenic (99%) and iron (98%). In addition, only coco-peat significantly removed boron.

Huang et al. (2011) suggested that HSSF CW should be combined with ultrafiltration–reverse osmosis (UF/RO) as a heavy metal wastewater treatment system. The CW-UF-RO treatment system provides stable treatment effects. The CW treatment significantly decreased fouling of the RO membrane, obviating the need for chemical cleaning.

Peruzzi et al. (2011) tested the stabilization of the heavy metal sludge using reed bed sludge treatment wetlands. After 20 days of dehydration and treatment, the sludge became more stable than untreated sludge, which can be used for agricultural purposes.

Soda et al. (2012) investigated the heavy metal uptake of seven aquatic plants in a FWS CW. The aquatic plants in the experiment exhibited high removal rates for Fe, Cu, Zr, Ag, Sn, and Au. The study also investigated the bioconcentration factors of several metals in two plant species (*Acorus gramineus* and *Cyperus alternifolius*).
Luca et al. (2011) investigated the metal retention and distribution in the sediment of a 5-year-old FWS CW. The stability of the metal compounds in the sediment allows the FWS CW to continue retaining metals in fractions.

Table 3. Papers that mainly focused on heavy metals. Studies in bold font are described with more detail in subsequent sections.

<table>
<thead>
<tr>
<th>Description of study</th>
<th>Type of wetland</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investigated the capacities of gravel, coco-peat, zeolite, and limestone as substrates for treating Fe, As, and B in VF CW</td>
<td>VF CW</td>
<td>Allende et al. (2012)</td>
</tr>
<tr>
<td><strong>Tested the feasibility of HSSF CW combined with ultrafiltration/reverse osmosis in an advanced heavy metal wastewater treatment</strong></td>
<td>HSSF CW</td>
<td>Huang et al. (2011)</td>
</tr>
<tr>
<td>Assessment of a 5-year-old free water surface wetland for metal treatment and analysis of metal retention and distribution in sediment</td>
<td>FWS CW</td>
<td>Luca et al. (2011)</td>
</tr>
<tr>
<td>Investigated the stabilization of sludge in reed bed heavy metal treatment CW for agricultural application</td>
<td>Sludge treatment CW</td>
<td>Peruzzi et al. (2011)</td>
</tr>
<tr>
<td><strong>The study tested the metal uptake capacity of 7 aquatic plants.</strong></td>
<td>FWS CW</td>
<td>Soda et al. (2012)</td>
</tr>
</tbody>
</table>

3.4 BOD, COD, and removal of other contaminants

The studies in Table 4 investigated the removal of other kinds of pollutants, as well as BOD and COD. Two of the investigations are about vegetation. Caseilles-Osorio et al. (2011) evaluated *Eriochloa aristata* and *Eleocharis mutata* under tropical conditions. The results show that the rhizosphere of *E. aristata* and of *E. mutata* enhances the removal of COD, BOD, and other pollutants. Taylor et al. (2011) tested 19 species for COD removal under seasonal effects. The study showed that vegetation increases the removal rate of gravel wetlands especially at low temperatures.

Stefanakis et al. (2011) investigated the effects of design factors for COD and BOD reduction, such as loading, resting period, temperature, porous media, vegetation, and aeration. The results indicated that vegetation plays an important role in pollutant removal. However, the different species exhibited no significant differences.

Welz et al. focused on winery wastewater treatment wetland. They found that increasing the priming of ethanol wastewater enhances the biodegradative capacity of the VF CW for a long time.
3.5 Other factors of CW construction

In Table 5, three studies involving other factors related to wetland technology are listed, including the effects of the heterogeneous distribution of the hydraulic conductivity in wetland design, greenhouse gas estimation of treatment CW, and a simulation of the recovery capacity of recirculating vertical flow CW. These studies did not directly involve the removal ability of treatment wetlands. They also investigated the factors in wetland design and management that may affect removal efficiency.

Table 4 Papers focusing on other pollutants, as indicated by COD and BOD.

<table>
<thead>
<tr>
<th>Description of study</th>
<th>Type of wetland</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assessment of two macrophytes (<em>Eriochloa aristata</em> and <em>Eleocharis mutate</em>) in</td>
<td>Mesocosm-scale</td>
<td>Caselles-Osorio et al. (2011)</td>
</tr>
<tr>
<td>mesocosm-scale CW for sanitary wastewater treatment in tropic condition in</td>
<td>HSSF CW</td>
<td></td>
</tr>
<tr>
<td>removing organic matter and other pollutants</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimating the removal of organic matter and emerging pollutants via statistical</td>
<td>Mesocosm-scale</td>
<td>Hijosa-Valsero et al. (2011)</td>
</tr>
<tr>
<td>modelling</td>
<td>CW</td>
<td></td>
</tr>
<tr>
<td>Investigation of the effects of design and operation wetland characteristics:</td>
<td>Mesocosm-scale VF</td>
<td>Stefanakis et al. (2012)</td>
</tr>
<tr>
<td>loading, resting period, temperature, porous media, vegetation and aeration.</td>
<td>CW</td>
<td></td>
</tr>
<tr>
<td>Tested seasonal effects (temperature, climate) of 19 plants species in reducing the</td>
<td>HSSF CW</td>
<td>Taylor et al. (2011)</td>
</tr>
<tr>
<td>COD and compared their efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investigated biodegradation and mineralization of ethanol wastewater in HSSF-VF</td>
<td>HSSF-VF hybrid</td>
<td>Welz et al. (2011)</td>
</tr>
<tr>
<td>hybrid CW after increased priming</td>
<td>Mesocosm-scale CW.</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Papers regarding other factors related to constructed wetlands technology.

<table>
<thead>
<tr>
<th>Description of study</th>
<th>Type of wetland</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finding suitable method for incorporating the heterogeneous distribution of hydraulic</td>
<td>HSSF CW</td>
<td>Brovelli et al. (2011)</td>
</tr>
<tr>
<td>conductivity into the design phase</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assessed greenhouse gases (GHG) during the construction and operation stage of CW</td>
<td>Pilot-scale VF CW</td>
<td>Chen et al. (2011)</td>
</tr>
<tr>
<td>Recovery capacity simulation of a recirculating vertical flow CW</td>
<td>Recirculating vertical flow CW</td>
<td>Zapater et al. (2011)</td>
</tr>
</tbody>
</table>

4 Enhancement of nitrogen removal
4.1 A subsurface wastewater infiltration system

Li et al. (2011a) was done in a subsurface wastewater infiltration system (SWIS). In this system, nitrification and denitrification are the two core processes in N removal and nitrification is limited by temperature, dissolved oxygen (DO) availability, pH, and alkalinity. During nitrification, \( \text{NH}_4^+ \)-N is oxidized into \( \text{NO}_3^- \), which is highly dependent on oxygen supply, with DO levels lower than 4.6 mg/L almost completely preventing nitrification in the system. Furthermore, if the sewage column flows continuously, which is common in treatment wetlands, the substrate may become anaerobic. In addition, providing carbon source in the substrate limits denitrification. In the SWIS, decomposition generally happens in the upper layer, which may limit the carbon source in the lower part and then decrease denitrification. Therefore, adding oxygen in the upper part for nitrification and providing anaerobic carbon-rich in the lower part for denitrification enhances N removal in the SWIS. The constructed subsurface wastewater infiltration system (CSWIS) enhances denitrification, according to the direct shunting distribution of some sewage into the lower part, and improves nitrification by intermittent operation mode. The objectives of the study are as follows:

1. To test the effect of carbon source supplement on N removal by shunting distribution in CSWIS
2. To assess the wetting-drying operation system on N removal
3. To evaluate the CSWIS

The sewage investigated in this experiment was domestic wastewater collected from two families. The sewage was pretreated in a septic tank to remove the solid pollutants and minimize clogging before flowing into the system for final treatment.

In the investigation, an intermittent operation mode was used to transfer oxygen passively, wherein the sewage continuously flows for 24 h. Then, the wetting-drying ratio (WD) was controlled as \( \propto \) (termed as continuous feeding mode), 1.0, 0.5, 0.3, and 0.25, with the subsequent drying period of the intermittent operation mode lasting 0, 24, 48, 72, and 96 hours. After the drying period, the cycle of wetting-drying mode is restarted from the 24-hour continuous flow.

The CSWIS was 1.2 m wide and 1 m deep, as shown in Figure 1. The CSWIS substrate was 65% brown soil mixed with 30% coal slag and 5% activated sludge. The inlet pipe was placed at a depth of 30 cm. The bottom of the CSWIS was covered with waterproof materials to keep the sewage flowing inside the system. A part of the wastewater was introduced at 50 cm and at 60 cm depths to increase the denitrification rate. The shunting ratios between the flow in the upper pipe at 30 cm depth and the lower pipe at 50 cm or at 60 cm depth were \( 1:1, 1:2, 1:3, 2:1, \) and \( 3:1 \) (Li et al., 2011a).

The result confirms that CSWIS is effective in removing N and other pollutants from
domestic wastewater. In the continuous operation system, which has a 0 h drying time, the NH$_4^+$-N removal rate was 75.2% ± 0.4%. However, in the intermittent operation system, the NH$_4^+$-N removal rate was 86.2% ± 1.5% at a WD ratio of 1.0. Moreover, at a WD ratio of 0.25, the NH$_4^+$-N removal rate increased to 95.9% ± 0.4%, the highest among the rates at all WD ratios. The results confirm that the intermittent operation mode significantly enhances N removal in CSWIS. Additionally, at a shunting ratio of 1:1 between the upper pipe and the lower pipe, the total N removal significantly increased with increasing nitrification and denitrification, which suggests the highest rate among the five ratios. However, the NO$_3^-$ removal rate did not significantly increase and the difference between 50 cm and 60 cm was not significant. The results show that the average removal rate in the CSWIS at a shunting ratio of 1:1 between 30 cm and 50 cm and a WD ratio of 1.0 were 87.7% ± 1.4% for NH$_4^+$-N, 70.1% ± 1.0% for TN, 84.8% ± 1.3% for COD, and 85.1% ± 2.0% for TP at a hydraulic loading of 0.081 m$^3$/(m$^2$ d). These results are almost seven times more than the treatment rates without the shunting distribution and intermittent operation mode (Li et al., 2011a).

![Figure 1. Profile of a constructed subsurface wastewater infiltration system (Re-drawn from Li et al., 2011)](image-url)

**Comments:**
The results show that the SWIS is efficient in treating N, P, and COD. Although SWIS is not really a wetland, it can be considered a special wetland because of its similar removal processes and abilities. However, the shunting system was not clearly described in the article, which may become a problem in relevant design and result.
analysis. Based on the characteristics of the SWIS, it is mainly used for treating domestic sewage. Domestic sewage is commonly produced daily, which may obstruct the wet-drying process. The CSWIS used in the investigation was a laboratory-scale system. If more than one distributing pipe is used in the system, the pipes may be able to work alternately. Similarly, when half of the pipes are distributing sewage into substrate, the remaining pipes stop working to provide a drying period. This may be a possible way to implement intermittent operation mode in real treatment wetland.

4.2 A study of FASSTT LWA substrate

Białowiec et al. (2011) investigated N removal using a novel substrate. The common media for reed beds in treatment wetlands consist of gravel and sand. Clogging, which decreases the treatment efficient, is the main problem in this type of wetlands (Nivala et al., 2012). According to Białowiec et al. (2011), earlier experiments show that clogging is limited by media and wastewater characteristics, and light expanded clay aggregate (LECA) was found to increase the growth of biofilm and decreases the risk of clogging. Based on earlier studies, LECA has higher nitrification and filtration than other substrates, such as plastic Norton rings. LECA is also effective for treating P in wetlands. The pre-investigation conducted by the study indicated that fly ash from sewage sludge thermal treatment (FASSTT) light weight aggregates (LWA) is one of the reasonable substrate replacements for LECA (Bialowiec et al., 2009). Białowiec et al. (2011) investigated the N removal capacity of 30 laboratory-scale vertical flow constructed wetlands with FASSTT LWA and gravel substrates. Three key processes were done in this experiment to assess the FASSTT LWA:

1. Thirty laboratory-scale vertical flow constructed wetlands were built using high water permeability coefficient–FASSTT LWA and gravel as substrate.
2. The upper (FASSTT LWA) and lower (gravel) layer ratio was increased to test the maximum treatment ratio.
3. Common plant reeds from the constructed wetlands were used to test the feasibility of reeds uptake.

The results of the study show that the N removal in the FASSTT LWA media wetlands was sustainably effective. The nitrification in the wetland was unlimited and the ammonia N concentration decreased by 99%. In the pre-investigation, the FASSTT LWA had a higher N removal efficiency than sand filters. Reed beds also highly influenced N removal with the exception of sand filters. The influence of reeds was significant in the system, which consisted of 25 cm of FASSTT LWA (upper layer), and 75 cm of gravel (lower layer). In this condition, the total N removal efficiency was 59.5%, the highest removal rate among all the substrates combinations tested (Białowiec et al., 2011).

Comments:
The study presented the maximum total N removal rate of the FASSTT LWA-gravel substrate CW. The VF CW with purely FASSTT LWA substrate exhibited a lower
total N removal rate. Two possibilities may explain this phenomenon, namely, the gravel layer supported anaerobic conditions for denitrification or the gravel had a lower water permeability coefficient, which retained the wastewater in the lower layer for a longer period and provided a longer hydraulic retention time.

The result is based on the planted VF CW and the unplanted VF CW, which had no significant removal rate when the thickness of FASSTT LWA layer is increased. This phenomenon may confirm that FASSTT LWA enhances plant uptake. In addition, the wastewater did not contain large amounts of organic carbon, which indicates that the carbon for denitrification may have been supplied by the roots. These two hypotheses were mentioned but unclarified in the article.

4.3 Wood mulch and zeolite substrate in a hybrid wetland system

Saeed and Sun (2011b) investigated the denitrification ability of wood mulch and zeolite substrates in complex wetlands system. They built three hybrid CW systems (1, 2, and 3). Each wetland system was combined with a vertical flow (VF) wetland, which employed eucalyptus wood mulch as the main substrate (wetland A), a horizontal flow (HF) wetland with gravel as the media (wetland B), and a VF wetland using zeolite as the substrate (wetland C). The depths of the two VF wetlands were 0.995 m and the depth of HF wetland was 0.6 m. The synthetic wastewater was treated in wetland A, allowed to flow into wetland B, and then into wetland C. Three systems were controlled as different operation conditions. System 1 was maintained with a fixed flow and a stable contaminant concentration. System 2 was maintained with a fixed flow but with fluctuating hydraulic loading. System 3 was maintained with fixed hydraulic loading but with a fluctuating influent pollutant concentration.

The results show that wetland A has an 11.7 g/(m² d) average NH₄⁺-N removal rate and a 7.2 g/(m² d) to 15.8 g/(m² d) average TN removal rate. The data show that both nitrification and denitrification occurred in the VF wetlands with wood mulch substrates. Wetland B, the HF wetland, exhibited a significant COD reduction rate. The average COD reduction rate in wetland B exceeded 67.0%. The NO₃⁻-N removal in system B reached 64.0%. The last VF wetland, which had a zeolite medium, removed over 90% of the NH₄⁺-N in its water column. By contrast, the zeolite wetland had a low NO₃⁻-N treatment rate, which may be caused by the high BOD reduction rate in the substrate. Based on earlier investigations, the high BOD reduction rate in the substrate limits the organic carbon supplement in NO₃⁻-N denitrification, which may account for the low NO₃⁻-N removal rate in the substrate. In addition, the DO concentrations in the effluent of the three wetlands were similar to the first, which confirmed that the nitrification in the system was not limited by oxygen. The NH₄⁺-N was treated completely in the third VF wetland with the zeolite medium because of adsorption (Saeed and Sun, 2011b).
The operation condition test confirmed that the fluctuating hydraulic loading and influent pollutant concentration did not significant affect the performance of the two VF CWs. In contrast, the NH\textsubscript{4} removal in the HSSF CW was highly dependent on pollutant loading. The increase in the N load in the HSSF decreases oxygen supply from the atmosphere, which in turn, limits nitrification.

Comments:
The investigation demonstrated the treatment efficiency of the VF-HSSF-VF CW system. An earlier investigation confirmed that organic substrates are unsuitable for HSSF CWs. The organic substrate in HSSF CW increases the organics, P, and suspended solids in the wastewater (Saeed et al. 2011a). The investigation also confirmed that VF CW with an organic matter substrate is more stable and efficient in treating N than conventional gravel HSSF CW. Therefore, the hybrid CW system in the investigation had a reasonable selection of substrate.

Additionally, the sewage in the wastewater that flowed into the third VF wetland may have had low NH\textsubscript{4}+ and NO\textsubscript{3}N. Although the results showed the capacity of the zeolite substrate VF wetland, its ability to treat wastewater with high N concentrations was not confirmed.

4.4 A baffled subsurface flow constructed wetland

Tee et al. (2012) investigated a baffled subsurface-flow constructed wetland with many baffles inside the horizontal subsurface flow (HSSF) wetland, as shown in Figure 2. In this design, the HSSF wetland was separated into many small VF rooms. A baffled subsurface-flow wetland provides both aerobic and anaerobic conditions for treating N via nitrification and denitrification. In the investigation, two-thirds of the rooms were filled with raw rice husk and the remainder was filled with pea gravel. Raw rice husk allows vegetation to grow deeper roots and then form micro-aerobic zones. The study tested the ammonia removal capacity of this baffled HSSF wetland. Four wetlands were compared in the investigation. Two of them were baffled and the others were unbaffled. One of the baffled and the unbaffled wetlands were planted with cattails (\textit{Typha latifolia}) to test the contribution of plants in the wetlands. These wetlands were designated as NDP (baffled planted), ODP (unbaffled planted), ND (baffled without plants), and OD (unbaffled without plants).

The retention rate was highly dependent on the hydraulic retention time (HRT). At an HRT of 5 days, the NH\textsubscript{4}+ was almost completely removed in the NDP. At HRTs of 2 days, the removal rate in the NDP was whereas that at an HRT of 3 days was 73.8%. The NH\textsubscript{4}+ removal rate in ODP was also 96% at an HRT of 5 days. At an HRT of 2 days, the NH\textsubscript{4}+ removal rate only reached 55% whereas that at an HRT of 3 days was 70%. In the comparison test, the unplanted (ND, OD) units exhibited much lower removal rates than the planted units; the simple unbaffled HSSF wetland (OD) had a lower efficiency for removing NH\textsubscript{4}+N, which was only 42% to 49% under an HRT of
5 days. Moreover, COD also showed a significant removal rate in the baffled HSSF wetlands (NDP, ND) which was about 89% ± 4% at an HRT of 5 days. By contrast, the unbaffled HSSF wetland (ODP, OD) only got a removal rate of 59% ± 2% at an HRT of 5 days. In all the tested wetlands, the TON removal rate, which is the NO$_2^-$ and NO$_3^-$ removal rate, reached 99% at an HRT of 3 days. The result confirms that the new wetland system is better than conventional unbaffled HSSF wetland in N removal. Plants are important for nitrate removal but they do not significantly increase the BOD (Tee et al., 2012).

Comments:
A laboratory-scale baffled HSSF wetland system was tested. In the CW, the up and down system may clog the wetlands. When the sewage flows to the top, the solids in the water column blocks the water. Gravity compounds the block more than in horizontal flow and vertical flow wetlands. A clogging test of the novel baffled HSSF CW should be done in further investigations. In addition, there is no cooperation investigation for rice husk substrate. Therefore, the contribution of rice husk substrate was unclear. This wetland is better for N removal and certainly more complex than common HSSF wetlands. The cost of this wetland may be too high even for domestic wastewater. Further investigations on decreasing the cost of baffled wetlands should be done.
5 Phosphorus removal and recovery

5.1 A recovery concept with aluminium sludge as substrate

Phosphorus is one of the most important treatment targets in constructed wetlands. Zhao et al. (2011a) presented a new concept about P treatment and recovery, which describes a system that reuses the by-product alum sludge from a water treatment plant as wetland substrate for domestic wastewater treatment. Alum sludge is commonly disposed in landfills, with little beneficial value. The article constructed a
novel system that combines water treatment and wastewater treatment with alum sludge, as presented in Figure 3. First, water is collected from rivers into the water treatment plant. In the water treatment plant, the river water is treated to produce potable water and then sent to families and industries. The large amount of alum sludge produced by the treatment processes in the water treatment plant is transferred to a constructed wetland system as the substrate for the wetlands, which is then used to treat domestic sewage. Finally, the wastewater from families and industries are treated in the alum sludge-based CW and the effluent is diverted into rivers. In this system, alum sludge is reused to treat P and other pollutants in wastewater.

The feasibility of this system was tested by Zhao et al. (2011a). They conducted a field study of a pilot-scale alum sludge–based FWS tidal flow CW. The CW was combined with four down flow wetland cells. The wetland cells were 1,100 L plastic bins connected with submersible pumps. In the substrate, the bottom level (10 cm) was filled with gravel and the remaining space was filled with alum sludge cakes made from the alum sludge collected from a water treatment factory. The common reed *Phragmites australis* was planted on the top of the wetlands. The treated wastewater partly consisted of wastewater from a farm with over 2,000 sheep, pigs, cattle, and horses. The wastewater was pretreated to reduce solids before it was introduced into the wetland.

The wastewater in the wetland flowed in three cycles each day. Every cycle consisted of a 4-hour flowing period and a 4-hour wet period. Effluent samples were collected every week. The results illustrate that the alum sludge–based CW was efficient in treating BOD, COD, NH$_4^+$-N, TN, P, and total P (TP). The removal rates were 57%–84%, 36%–84%, 49%–93%, 11%–78%, 75%–94%, and 73%–97%, respectively (Zhao et al., 2011a).

After determining the removal capacity of alum sludge-based wetland, the authors further investigated on the recovery of the alum sludge (Zhao et al., 2011b). They methods for recovering P from alum sludge in the wetland. The general process of P removal entailed phosphate precipitation as iron or aluminium salt in the activate sludge, which binds P to alum

The P recovery experiments from dehydrated alum sludge cakes (DASC) suggested a three-step plan:
(1) P extraction from the used DASC;
(2) Decoloration of the P-extraction leachate; and
(3) Precipitation of the phosphates.

The third step of the recovery process in the investigation is shown in Figure 4. An effective and consistent method for recovering P and Al from the DASC, which were used as substrate in the wetlands, is shown (Zhao et al., 2011b).
Comments:
These two investigations proposed the reuse of alum sludge as substrate in CW, and then the recovery of Al and P from the CW substrate for reuse in a water plant and as fertilizer. This concept is a highly completed system for both wastes recycle and wastes treatment. Therefore the concept is match with the image of the multiple benefits of treatment wetlands.

The recovery is based on the P treatment historical substrate, which is hard to measure in actual studies. This problem prevents the determination of the substrate recovery period.

Figure 3. Conceptual illustration of beneficial integration of alum sludge into wastewater treatment (Re-drawn from Zhao et al., 2011a).
Figure 4. P precipitation processes (Re-drawn from Zhao et al., 2011b).

5.2 Fragmented limestone substrate
Mateus et al. (2012) investigated the capacity of fragmented limestone as a substrate for P removal in constructed wetlands. Since scientists began to study P removal in constructed wetlands, the substrate plays one of most important roles. Earlier studies indicated that the need for huge amounts of substrate materials increases the cost of P treatment in constructed wetlands, which limits the spread of ecologically friendly engineering technology. Therefore, the authors tested materials from industrial wastes and natural minerals. Limestone is a decorative material used in civil construction. Every year, people exploit huge amounts of this material for civil engineering works, much of which is wasted. Using this material as a substrate in the constructed wetlands is a quite reasonable choice to treat this pollutant. Therefore, in this investigation the adsorption ability of fragmented Moleanos limestone was evaluated. Moleanos limestone is extracted around Moleanos and Aljubarrota by a few small to medium companies. The test consisted of an adsorption test and pilot-scale HSSF wetland experiments. The adsorption test indicated that FML has similar adsorption ability as other common mineral substrate materials. Although materials, such as blast furnace slag, burnt oil shale, and alum sludge have much higher theoretical maximum adsorption rates and lower half saturation concentrations, FML has a lower production cost and a lower risk of clogging than the other substrates. Pre-investigations confirmed that other substrate materials release contaminants into the treated wastewater. By contrast, the author claimed that FML causes internal loading. In addition, the pilot-scale HSSF wetland experiments lasted for 18 months. The results of the pilot-scale HSSF wetland experiments confirm that the average P removal rate by FML is 60% ± 7% at a hydraulic loading rate of 40 L/(m² day) ± 4 L/(m² day), which is higher than the average removal rate reported by Kadlec in 2008 (Mateus et al., 2012).

Comments:
Although the result demonstrated high P removal rates, its significant adsorption and lower price make FML a reasonable option for substrate in P treatment CW. The study was limited to Moleanos limestone, so the feasibility of other kinds of limestone was not determined. In the investigation pure FML substrate CWs exhibited significantly better performance than other substrates. The capacity of the FML mixture and other media was also unclear. Therefore, before the application of FML substrate, more assessments need to be done.

6 Wetland contributions in heavy metal removal

6.1 Advanced treatment of metal wastewater in constructed wetland/ ultrafiltration/ reverse osmosis
Huang et al. (2011) compared an ultrafiltration (UF)/reverse osmosis process (RO) system with a constructed wetland (CW)/UF/RO system to assess constructed wetlands in UF/RO systems for advanced treatment. The UF process is mainly used for the advanced treatment of suspended substances in metal processing wastewater. By contrast, the RO process is used to remove large molecules and ions. Considering the risk of biological contamination of the RO membranes and the requirement of wastewater quality, the RO process is generally used as advanced treatment. The systems were constructed as shown in Figure 4. In system A, the wastewater is first treated in the UF process and then directed into the RO process. The comparison test was done in system B, where wastewater is first introduced into a subsurface flow constructed wetland and then treated in the UF/RO system. Based on the result, the CW effectively reduced the turbidity, COD, and NH$_4^+$-N. The CW substrates in the investigation were gravel and manganese ore. In the wetland, iron and manganese were effectively removed, with 96.9% and 92.5% removal rates, respectively. In the investigation, the surface of the manganese substrate was covered with a biofilm, which was the key site for iron and manganese removal. In the wetland, iron was oxidised and manganese was adsorbed onto the biofilm and then oxidised by manganese-oxidizing bacteria. By comparison, the UF/RO system was extremely good in reducing turbidity, conductivity, sodium, and alkalinity. On the other hand, COD and NH$_4^+$-N were incompletely eliminated. Therefore, the UF/RO system was unsatisfactory and adding the constructed wetland was necessary to decrease the fouling and the final pollutant concentration in the outlet (Huang et al., 2011).

Comments:
The CWs commonly applied in metal wastewater treatment typically focused on advanced treatment. Highly toxic wastewater disrupts the biodiversity of the CW and then decreases the biochemical process (Kadlec et al., 2008). In this study, the author confirmed that CW is necessary for the primary treatment of the system, which is an unconventional idea. Although the CW was highly efficient in metal and N removal, the effect of long-term treatment with CW was unclear.

In the investigation, the composition of the biofilm on the surface of manganese was not tested. The result do not account for the production of the biofilm layer. The biofilm layer was the key factor in iron and manganese removal in the investigation; thus, the composition and the formation should be investigated.

Another limitation of the investigation is that the capacity of the CW was tested at an HRT of 1.5 days, which may be hard match with the treatment speed of a UF/RO system. Longer HRTs would significantly improve the performance and the treatment capacity at short HRTs should be confirmed.
Figure 5. Schematic diagrams of the UF/RO system and the CW/UF/RO system (Re-drawn from Huang et al., 2011)

6.2 Capacity of emergent plants for metal removal in CW

Soda et al. (2012) investigated the metal-processing wastewater treatment capacity of CWs and two major emergent plants in CWs (*Acorus gramineus* and *Cyperus alternifolius*). In the investigation, several species of vegetation were planted in the main FWS CW system; only two kinds of plants were planted in a small FWS CW for harvesting. The main FWS CW system was 20 m long, 46 m wide, and 0.3 m deep. The main FWS CW was constructed in four lanes, as shown in Figure 5. First, the wastewater was led to the trickling filters. The trickling filters consisted of about 200 plastic containers of wood chips and rice chaff. No substrates were placed in the plant area and the plants were attached with plastic cubes fixed in the water. The roots of the plant were directly exposed to the wastewater. The results showed that the main CW removed 80% TOC, 18% TN, and 41% NH$_4^+$-N. Moreover, Fe, Cu, Zr, Ag, Sn,
Au, and Al were significantly removed in the main CW system.

Figure 6. Schematic diagram of the main CW (Re-drawn from Soda et al., 2012)

In the small laboratory-scale FWS CW, only *A. gramineus* and *C. alternifolius* L. were planted. Two lanes were built to support the wastewater flow into the room of *A. gramineus* and *C. alternifolius* L. After 3 months of investigation, the plants were harvested to analyse their metal content. The results show that the metal concentrations in the plants were not significantly higher than that in common plants. Therefore, plant uptake was not the key factor in metal treatment. In the two wetlands, the HRT was 3 hours. The CW planted with *A. gramineus* slightly removed Al (24.6%), Zn (17.6%), Zr (22.5%), and Bi (8.9%). By contrast, the metal removal rates of CW planted with *C. alternifolius* L. were not significant, which were Al (26.7%), Cr (12.0%), Mn (7.1%), Fe (13.4%), Zn (24.2%), Zr (22.5%), Sn (5.2%), Pb (18.8%), and Bi (21.8%) (Soda et al., 2012).

Comments:
In this investigation, the main CW was covered with aquatic vegetation. However, the authors did not describe the theory underlying vegetation arrangement. In the main CW, some aquatic plants were planted in two different rows. Finally, all the water columns were directed into the same effluent. This design is strange for the assessment of plant uptake.
In common FWS CWs and HSSF CWs, metals may combine with organic molecules to facilitate plant uptake. Therefore, the low metal removal rate and TN in the main CW may be due to the absence of substrate. In the CW, the wastewater directly flowed through the roots, which offer aerobic conditions and shortens the HRT. The lack of substrate in the CW may lead to low uptake operation and limit the pattern of the metals. This investigation did not present the average levels of plant uptake.

6.3 A study on metal compounds and retention in the sediment

Luca et al. (2011) tested the metal distribution in the sediment of a 5-year-old FWS wetland. The metal concentration in the inlet was significantly increased and the owners were concerned with the treatment ability of the wetland. The constructed wetland is located in Santo Tomé, Santa Fe, Argentina, which was built for the Bhco Argentina tool factory. In the study, samples were collected in August (winter), October (spring), and May (autumn) 2008. The preinvestigation determined the treatment capacity of the FWS wetland. The COD and the BOD retention rates were 81% and 90%, respectively, in the outlet. The soluble reactive P was reduced by 78% and the total P decreased by 52%. The N removal rate was approximately 85%. The reduction rates for Fe, Cr, Ni, and Zn were 98%, 90%, 59%, and 57%, respectively. The study concluded that the wetland was still effective in removing nutrients and metals after 5 years.

After the capacity test, the investigation focused on the sediment analysis. In the spring, the Cr, Ni, and Zn decreased in the sediment via vegetation uptake. The metal concentrations in the sediment decreased with depth. The metal concentration in different compartments of the system indicated that sediment is important in metal storage in the wetland treatment. In the investigation, the metal concentrations were tested with the sampling position. The results demonstrate that metal concentrations are higher in roots and rhizomes than in other parts of the plants. This phenomenon confirms that plant uptake occurs during metal removal in the sediment.

The metal partitions in the sediment were complex. Three patterns were tested in the investigation: bound to carbonates, bound to Fe–Mn oxides, and bound to organic matter. Cr was mainly bound to Fe–Mn oxides, Ni was mainly associated with the carbonate fraction, Zn was mainly bound to the carbonate fraction, and Fe was mainly bound to the residual fraction. The investigation also found an active layer 10 cm beneath the sampling layer of the wetland that functions in exchange storage part of the sediment (Luca et al., 2011).

Comments:
The 5-year-old FWS wetland was still removing pollutants, including COD, BOD, P, N, and metals. The removal rates were very high, even compared with wetlands with shorter working time. This result confirms that working time does not limit FWS
wetlands. After 5 years of operation, the removal rate for many pollutants has not significantly changed.

In the investigation, the metals reacted with the sediments to form different compounds. Most of the compounds in the sediment were stable and were removed by plant uptake (Luca et al., 2011). Therefore, investigating the compounds assimilated by plants will help determine the metal removal processes of plant uptake.

7 Discussion

Although the recent investigations have varying objectives, the methods they assessed can be summarised as follows: hydraulic loading control, substrate selection, flow type of CW, and vegetation selection. These four factors are the key factors that determine the treatment capacity of CWs.

Hydraulic loading control

In the investigations that focused on N removal, the hydraulic loading control was tested as method to enhance nitrification and denitrification. In tidal flow CWs, the oxygen supply is unlimited because of the flooding-drying cycle (Wu et al., 2011). Similarly, in SWIS, a wet-drying operation cycle also promotes nitrification (Li et al., 2011a). In the investigation, the highest removal performance was achieved at a wet-drying ratio of 0.25:1. This result confirms that long-term drying increases the TN removal rate. By contrast, the denitrification process is related to the carbon supply. In an SWIS, the shunt wastewater distribution system effectively solves the supply of carbon (Li et al., 2011a). In tidal flow CWs, the organic-rich wastewater leads to higher N removal rates (Hu et al., 2011). This method is also efficient for BOD treatment. In HSSF-VF hybrid CWs, increasing the priming ethanol wastewater enhances the biodegradative process in the CW (Welz et al., 2011). However, effects of hydraulic control on P and metal removal have not been investigated.

Substrate selection

Substrate is a key factor in research on N, P, and metal removal, as well as BOD and COD reduction. Porous substrates have gained increasing attention for N removal. Porous substrates such as rice husk and FASST LWA allow the roots of vegetation to grow deeper, which promotes plant uptake and decreases the risk of clogging (Białowiec et al., 2011; Tee et al., 2012). Additionally, in these two investigations, the substrate was a mixture. The maximum removal rate was achieved in the 25 cm FASST LWA and 75 cm gravel substrate (Białowiec et al., 2011). This result demonstrates the advantage of mixed substrates.

Some organic media such as wood mulch are unsuitable for HSSF CWs because they increase the organic matter, P, and suspended solids in the wastewater (Saeed et al.
This result is based on an assessment of a wood mulch–gravel substrate in a conventional HSSF CW. However, these problems did not occur in the rice husk–gravel substrate in baffled HSSF CW (Tee et al., 2012). In the VF CW, wood mulch exhibited a high TN removal rate (Saeed et al. 2011a).

By contrast, the substrate for P and metal removal commonly has a significant adsorption capacity. Zeolite is highly adsorbent for both P and heavy metals (Fe and As) (Allende et al., 2012; Bruch et al., 2011). In addition, in the mixed substrate, zeolite enhances the hydraulic retention time by increasing the capacity for shrinkage and swelling (Bruch et al., 2011). Cost is another important requirement in substrate selection. Fragmented Moleanos limestone is an inexpensive medium. Although the removal performance and adsorption ability of FML are not as outstanding as other substrates, it is a reasonable option for the P treatment of wetlands (Mateus et al., 2011).

A recovery concept was presented and confirmed by Zhao et al. (2011a). In the concept, alum sludge cakes from drinking water treatment plants were used as a substrate for HSSF treatment wetlands. The whole concept provides an environmentally friendly treatment cycle (Zhao et al., 2011a; 2011b).

Flow type of CW
The capacity of conventional flow types of CWs has been confirmed by numerous investigations. Novel CWs and hybrid CWs were assessed in 32 studies. Hybrid CWs provide both aerobic and anaerobic conditions for nitrification and denitrification. VF-HSSF hybrid CWs are more stable and efficient for N, BOD, and COD treatment than simple VF and HSSF CWs (Saeed et al., 2011b). Similarly, the combination of flow type in one CW promotes both nitrification and denitrification (Tee et al., 2012). In these two kinds of CWs, nitrate and ammonia are completely removed from the sewage columns. Furthermore, the removal rates of COD and BOD are also significantly higher than those in single flow type CWs (Tee et al., 2012; Saeed et al., 2011b).

Investigations involving single FWS CWs are mainly about sediment. Stabilisation of the sediment is very important in FWS CWs. After long-term treatment, the risk of intercontamination by the pollutant-rich sediment was assessed in both P and heavy metal treatment CWs. The investigations confirmed that the heavy metal compounds in the sediment are stable even for 5 years of long-range treatment (Luca et al., 2011). By contrast, after long-term treatment, the sediments in the P treatment CWs release SRP flux into the water column (Palmer-Felgate et al., 2011). Surface alum is added and soil is dried to prevent this phenomenon (Lindstrom et al., 2011). Reed beds are also a significant countermeasure for decreasing internal loading. Unexpectedly, dredging does not prevent internal loading (Palmer-Felgate et al., 2011).

Plant selection
Plants have an important role in contaminant removal in CWs. In the planted VF CW, the removal capacity of N increases with the increase in the percentage of porous media in the substrate (Białowiec et al., 2011). This phenomenon does not occur in unplanted VF CWs. In FWS CW, plants also decrease the P internal loading from the sediment (Palmer-Felgate et al., 2011). Although the vegetation in metal treatment CWs provide plant uptake, the species of the plants has no significant effect on the pollutant removal rate (Soda et al., 2012; Stefanakis et al. 2011). In addition, the reed bed in sludge treatment CWs stabilises the heavy metal sludge and makes it safe for agricultural application (Peruzzi et al., 2011).

Seasonal factors limit plant uptake. In summer, plant uptake provides a higher removal rate than in winter (Taylor et al. 2011). Compared with unplanted CW, vegetation facilitates BOD and COD reduction, especially at low temperature (Taylor et al. 2011).

8 Conclusion

The wetland technology for wastewater treatment is continuously improving. Numerous papers and investigations about wetland technology have been published in the past year. Although all the studies reviewed in this paper focused on the enhancement of wetland treatment, a variety of methods were involved. Some studies were based on engineering technology and some were applications of chemical analysis methodology. The review is helpful in keeping updated with the current trends in the development of wastewater treatment wetlands.

In the studies, the vertical–horizontal hybrid flow CW was confirmed as a highly efficient CW strategy in the treatment of N, BOD, and COD. The vertical–horizontal hybrid CW has a stable operation capacity for treating fluctuating hydraulic loading and contaminant concentration. In addition, the nitrate and ammonia in the wastewater are completely treated in vertical–horizontal hybrid CWs. In vertical flow CWs, porous substrate is combined with conventional gravel substrate for highly efficient for N removal. The upper porous medium allows the roots of vegetation to grow deeper to promote plant uptake and organic supply. The lower gravel media facilitates filtration and adsorption processes. Organic substrates, such as wood mulch and rice husk, are inexpensive and suitable options for the upper porous media. However, the capacity of organic substrates in HSSF CWs is unclear and needs to be investigated further.

Compared with N removal CWs, investigations on P removal focus on FWS and HSSF CWs. In FWS P treatment CWs, internal loading is a common problem that decreases the quality of the effluent sewage. Recent studies indicated that reed bed and surface alum addition decrease internal loading in the sediment of FWS CWs. Additionally, dredging does not decrease the SRP flux released from the sediment.
Investigations about HSSF P treatment CW mainly focus on the substrate. P is not released by the atmosphere, and the P removed by CW is stored in the substrate. Therefore, the substrate of P treatment CWs entails a low cost and provides easy access. Fragmented Moleanos limestone was confirmed as an inexpensive substrate and it may be a reasonable option for wetlands close to populated areas. A new concept for building a sustainable system using alum sludge-based wetlands for P removal, and then the P and the alum sludge are recovered from the substrate in the sludge-based CW. This setup is a win–win strategy for both P removal and water plants, which provides an environmentally friendly project for CW application.

FWS CWs with common reeds is an economical option for heavy metal removal. Treatment using FWS CWs is stable and efficient even after longs treatment period (5 years). However, if the treatment requires both high removal efficiencies and small space, VF and HSSF CWs with fragmented limestone or zeolite are better choices. Another approach for treating heavy metals by CWs is by combining CW with other treatment systems. The efficiency of short-term primary treatment using HSSF CWs for sewage containing heavy metals has been proven. HSSF CWs significantly decrease the organic solids in sewage. However, the effects of long-term primary treatment with CW still need to be assessed.

Vegetation increases the removal rates of all wetland types for all types of pollutants. However, the species of the vegetation does not significantly influence the removal rates.

Further research is needed to explore the capacity of other porous substrates and the feasibility of combined substrates. Similarly, investigations on wet-drying hydraulic loading are needed to test other types of wetlands. Additionally, the effect of the environment should be tested in further assessments of wetland treatment.
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