Use of macrophyte plants, sand & gravel materials in constructed wetlands for greywater treatment

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Abstract. Greywater discharged without any treatments into drainage channels or natural water bodies will lead to environmental degradation and health risk. Local macrophyte plants combined with natural materials of sand and gravel have been used in a system of constructed wetland for the treatment of the greywater. This paper presents the results of some studies of the system carried out in Indonesia, Thailand, and Costa Rica. The studies demonstrate the success of the constructed wetland systems in removing some pollutants of BOD, COD, TSS, pathogen, and detergent. The studies resulted in the treated water in a level of treatment that fulfils the requirement of the local standards for wastewater reuse as irrigation water, fishery, or other outdoor needs.

1. Introduction

Greywater in developing countries is commonly discharged without any treatments into drainage channels, onto streets, on open grounds, or into natural water bodies. In low and middle income countries, greywater has been given the lowest priority in environmental sanitation management system compared to blackwater and solid waste management [1]. It leads to negative impacts on public health and aesthetic environment.

The wastewater in the cities in developing countries is typically discharged either into private septic tanks or directly into drainage channels. Many septic tanks may leak and are in direct contact with groundwater. Centralized wastewater treatment plants had been built in 12 cities in Indonesia. The wastewater treatment uses conventional technology systems which include aeration ponds, mechanically aerated lagoons, activated sludge systems, anaerobic sludge blanket systems, and rotating biological contact systems. The conventional wastewater treatment plant needs an extensive land, high investment and operational cost, technical trained persons, and a long time in the planning and implementation. The wastewater treatment plants are however inadequate to serve the need of urban sanitation as they only serve 10% of the Indonesian population. Consequently, untreated domestic wastewater which contributes 60% pollution will contaminate the natural waters [2].

It is understandably that sanitation is to be critical issues with polluted surface and groundwater [1]. It is getting worst with rapid urbanization and population growth, as well as the people environmentally-unfriendly activities. Meanwhile, the conventional wastewater treatment systems are
costly for developing countries. Hence, an alternative low-cost technology for wastewater treatment is significantly required.

For developing countries and particularly for those in the tropics, constructed wetlands (CWs) for wastewater treatment are potentially a good solution for treating domestic and industrial wastewater due to the simple operation and low implementation cost [3]. The CWs systems do not need to install wastewater treatment systems which require investment cost, power supply, replaceable spare-parts, skilled labors, operation and maintenance cost. The CWs is simple and cost-effective technologies which can only use local aquatic macrophyte plants and local sand or gravel materials. Unfortunately, in developing countries, the CWs had not been found widespread use [4]. This paper aims to present the results of the recent studies conducted in Central Java-Indonesia and some similar studies carried out by other researchers in West Java-Indonesia, Thailand, and Costa Rica. The other aim is to inspire the use of natural materials that are locally available for the application of CWs.

1.1. Constructed wetlands

Constructed wetlands (CWs) are engineered systems which are designed and constructed to mimic the natural process of wetlands. The systems take advantages of many of the same process that occurs in natural wetlands involving wetland vegetation (macrophyte plants), substrate (soil, sand, gravel), and associated microorganisms for treating wastewater. It covers complex processes involving physical, chemical, and biological mechanisms to remove various pollutants or improve water quality [5]. The synonymous terms of “constructed” include “man-made”, “engineered”, or “artificial”, or “treatment” wetlands [6]. The CWs with macrophyte plant roots, aquatic microbial communities, and a supporting mineral matter are effective at removing pollutants, such as suspended solids, dissolved and particulate organic matter, nitrogen, phosphorus, metals and photogenic organisms from wastewater [7].

The first experiment of wastewater treatment using wetland plants was conducted in 1952 by the German Scientist Dr. Seidel. Recently, the use of CWs systems for wastewater treatment have been more popular in many developed countries such as Germany, UK, France, Denmark, Austria, USA, and Australia; however, in developing countries the application of CWs systems is still limited [5,6].

According to wetland hydrology, the CWs are classified into surface flow (SF) and subsurface flow (SSF). The SF-CWs are similar to natural wetlands as they occupy shallow flow with low velocity above and within the media filter (substrates). In SSF-CWs, wastewater flows horizontally or vertically through the substrates. Hence, the SSF systems are classified into vertical flow (VF) and horizontal flow (HF). The combination of VF and HF is known as Hybrid CWs [5]. The CW basin commonly contains a combination of substrates and macrophyte plants. The process of purification occur during wastewater do contact with the surfaces of the substrates and the plant roots.

1.2. Material for constructed wetlands
1.2.1. Macrophyte plants

Many studies have demonstrated that macrophyte plants contribute to water treatment. Hence, the plants are an essential part in wetlands. The most important functions of the plants are related to their physical effects in the wetlands. The plants significantly transport oxygen to the root zone to allow the roots to survive in anaerobic conditions. The roots provide a huge surface area for the growth of bacteria colonies and other microorganisms which form a biofilm attached to the surface of roots and substrate particles. The root system of the plants maintains the hydraulic conductivity of the substrate [8, 9].

Macrophyte plants are commonly found in natural wetlands or riverbanks. In tropical developing countries, the macrophyte plants grow very well. The plants function which is not related to treatment performance is to provide a local green space; hence, the plants enhance the aesthetic appearance of the wastewater systems.

The aquatic macrophyte plants can be distinguished into 4 groups based on the form or location of the growth: emergent plants, floating leaved plants, submerged plants, and free floating plants. The emergent plants grow on water-saturated or submerged soil. Most of the above ground part of the plant
emerges above the water line and into the air. In subsurface flow (SSF) wetlands, their roots interact with the wastewater at the root zone only. In surface flow (SF) wetlands, the roots interact with the wastewater at the root zone, but provide an area for microbial attached growth. The floating leaved plants are rooted in submerged media. They have leaves and stems like they are floating in the water surface. The submerged plants grow with both stems and leaves within the water zone. These plants need sufficient water depth so that they can only be used within surface flow (SF) wetlands. The free floating plants are not rooted to the substrate. The plants can only be seen within the type of surface flow (SF) wetlands [10, 11].

Emerged plants such as Cattail, Bullrush, and Common Reed were recommended to be applied in SSF CWs [11]. The most frequently used plant in SSF CWs was Pragmatis australi (in Europe, Canada, Australia, Asia, and Africa), and the second most commonly used plant is Typha (in North America, Australia, East Asia, and Africa) [12]. In warm climates of South America, Africa, and Asia, [6] suggested the types of Macrophyte plants for SSF CWs that includes decorative plants (Papyrus sedges or Cyperus papyrus, Bamboo plants, Heliconia, Canna lily, Calla lily), very robust plants (Umbrella sedge or Cyperus albostraitus and Cyperus alternifolius, Dwarf papyrus or Cyperus hastens), and Broad-leaved cattail (Typha latifolia), as well as Species of grass native to the tropical grasslands (Napier grass or Elephant grass).

1.2.2. Substrates
Substrates used for CWs include soil, sand, gravel, crushed rock, other natural materials, as well as organic materials. They act for growing medium of macrophyte plants, support biochemical and chemical transformation, provide sites of removed pollutants, and allow the movement of wastewater [10]. Instead of natural material substrates, there are industrial by-product substrates such as slag, fly ash, coal cinder, alum sludge, hollow brick crumbs, limestone, or oil palm shell; and artificial products substrates such as activated carbon, light weight aggregates, compost, or calcium silicate hydrate [13]. However, for the application of SSF CWs for wastewater or greywater treatment in developing countries or countries in transition (warm to moderate climate), coarse sand is considered as the most suitable substrate [6]. The coarse sand was selected in relation to the hydraulic and organic loading which is the most critical design parameter in subsurface flow CWs.

2. Experimental
Application of CWs systems for two decades of experience shows that the systems are generally efficient in removing total suspended solid (TSS) and Biological Oxygen Demand (BOD), meaning that the effluent concentration less than 20 mg/L [14]. In developed countries, the aim of wastewater treatment is elimination of all pollutants like pathogen, nutrients, organic matter, and inorganic chemicals. However, in developing countries, the main goal is protection of the public health through control of pathogens to prevent transmission of waterborne disease [4]. For this purpose, application of CWs in developing countries is suitable since they can be efficient in removal of BOD and pathogens where removal of nutrients is often limited [15]. Therefore, this paper uses the indicators of the removal of BOD, COD, and pathogens (indicated by E. coli and total coli) to evaluate the performance of the CWs. The percentage efficiencies of the removal are known by comparing the removal of the pollutant at the outlet to the initial load of the pollutant at the inlet of the CWs.

A single horizontal subsurface flow (HF) constructed wetland with dimension of 1.7m x 0.7m x 0.7m (length x width x high) was used to investigate pollutant removal efficiency of greywater from a single house in the year of 2015. The study was conducted in the City of Surakarta, Indonesia, under an average temperature of 26°C. Substrates used in this study were river sand and gravel. The HF constructed wetland was filled to the total depth of 50cm which consists of 20cm long of gravels (Ø 1-3cm) at the inlet and outlet zones, and 130cm long of river sand (permeability 5.48 x 10^{-5} cm/sec) in the plantation zone. A local macrophyte plant of Cyperus papyrus was planted in the plantation zone of constructed wetland at 25 cm interval. Before entering the constructed wetland, the greywater was mechanically pre-treated in a sedimentation tank. To acclimatize the plants to the greywater, the
Greywater was discharged in the constructed wetland with gradual concentration from 25 to 100% within four weeks. With a hydraulic retention time of one day, the influent and effluent were collected and analyzed twice a month during three months of experiment. The parameters to be monitored were total suspended solid (TSS), 5 days biochemical oxygen demand (BOD$_5$), and chemical oxygen demand (COD). Since the type of household greywater at the study site typically contains a high concentration of detergent, this study included the detergent to be tested as well. The average result of the study is presented in the Table 1 as the latest study in 2015.

3. Result and discussion

To show that the local macrophyte plants and local natural substrates can perform successfully the treatment of domestic wastewater, the results of other experiments by other researchers in West Java-Indonesia, Thailand, and Costa Rica are also presented in the following table.

**Table 1.** The effective removal of pollutants in CWs with natural substrates and local macrophytes.

| Type & size of CW (L,W,H) & Area | Type of plant & Substrates | Country |
|---------------------------------|-----------------------------|---------|
| HF (1.7x0.7x0.7m) & Area: 1.19 m$^2$ | Cyperus papyrus & sand, gravel | Indonesia |
| VF (6x5x1.2m) & Area: 30m$^2$ | Phragmites Karka & sand, gravel | Indonesia |
| HF (2x1x1m) & Area: 2m$^2$ | Canna & Heliconia & gravel | Thailand |
| HF (14x1.2x0.6m) & (6x3x0.6m) & Area: 16.8 & 18m$^2$ | Coix lacryma-jodii & crush rock | Costa Rica |

The above studies use natural substrates (sand, gravel, or crushed rock) and macrophyte plants which are locally available in the study sites. From the economic point of view, these materials are considered cheaper than materials by product or artificial products substrates. All studies demonstrated that removal of organics, in term of BOD or COD, are high in all type of the constructed wetlands. The treatment efficiency of BOD and COD varied between 76.03-99.4% and 78.89-98.46% respectively, except COD removal studied in Thailand which varied between 42-83%. According to [16], it was still efficient as the influent wastewater has low concentration of COD which might be due to high degradation rate in the wastewater collection systems and in the settling tank before entering the constructed wetlands. The latest study in 2015 resulted in an effective BOD and COD reduction which are more than 98%. The inlet BOD concentration ranged between 496-850 mg/L, while that of the outlet ranged between 2.19-17.2 mg/L. It is below the threshold of 30 mg/L as set by US Environmental Protection Agency [17] and the Indonesian standard for wastewater reuse. In addition, the greywater from a household at the study site typically contains high concentration of detergent. Fortunately, the CWs system removed the detergent successfully, having a very high percentage efficiency of 99.86%.

The above studies resulted in a high removal of suspended solid (TSS or Turbidity). Suspended solid is removed primarily through the mechanism of sedimentation and interception [6]. In the latest study, solid removal efficiency ranged from 95.47% to 99.56% with an average reduction of 98.06%. TSS at the outlet varied between 2-10 mg/L, which is below the threshold of 30 mg/L as set by US Environmental Protection Agency [17] and the Indonesian standard for wastewater reuse. The study in Thailand used two types of macrophyte plants (Canna and Heliconia) and applied gravel only as the
filter media. It resulted in the well growth of both macrophyte plants [16] and very efficient removals of TSS for both plants which varied between 88-96%.

The constructed wetlands reduced both total and fecal coliforms. The average removal of total coliforms (in Indonesia) and fecal coliforms (in Costa Rica) were 99.45% and 99.99% respectively. It indicates a very high efficiency of the constructed wetland system on the removal of pathogen. The protection of the public health by means of controlling pathogens to prevent transmission of waterborne disease is the primary goal of wastewater treatment in developing countries [4]. In addition, the constructed wetlands are efficient in removal of BOD and pathogens while removal of nutrient is limited [11]. It was also stated by [5] that removal of phosphorus (TP) and nutrient (TN) in various types of constructed wetland is usually low, even recently some filtration materials by product have been tested in constructed wetland and resulted in a high removal of phosphorus; however, constructed wetlands were seldom built with phosphorus removal as a primary purpose of the treatment.

The above table shows that the study in Thailand resulted in low removal of phosphorus (6-35%) and nitrogen (4-37%). In contrast, removal of phosphorus and total nitrogen are high in the study of [18]. Substrates which contain high Ca, Al, and Fe have high phosphorus [19], so that the high removal of phosphorus in the study might due to the high amount of iron rich sand in the substrate used [18]. Nutrient removal is not one of the wastewater reuse criteria; hence, if the treated effluent is to be used for irrigation, then nutrient removal is likely to become unnecessary [15]. In addition to the study of [18], the average treatment efficiency of total coliform, NO$_3$-N, and PO$_4$-P represents the average effluent concentration of total coliform, NO$_3$-N, and PO$_4$-P of 4880 MPN 100/l, 1.36 mg/l, 0.07 mg/l respectively. These results are lower than that of Indonesia standard for irrigation water and fishery (10000 MPN 100/l, 20 mg/l for NO$_3$-N, 1 mg/l for PO$_4$-P).

The guidelines for wastewater reuse in Costa Rica place emphasis upon pathogen removal with the limit of fecal coliform of 1000 cfu/100 ml. Therefore, the study in Costa Rica used a longer hydraulic retention time (HRT) to be 7.9 days and resulted in a level of treatment that exceeds the requirement of the local standards for wastewater reuse in term of BOD average less than 10 mg/l and average fecal coliform of 122 cfu/100 ml with effective removal of fecal coli of 99.99% [15].

Houses in the cities of a developing country, like Indonesia, commonly have a limited open space. Table 1 shows the areas required for the constructed wetlands systems are relatively small (1.19 & 2 m$^2$) and moderate (16.8; 18; 30 m$^2$). Therefore, the constructed wetlands systems with the small and moderate areas are suitable to be applied as decentralized wastewater treatment systems on a single household and neighborhood respectively.

### 4. Conclusion

Natural materials of sand, gravel or crushed rock and local macrophyte plants used in the system of vertical or horizontal constructed wetlands have high performance for the treatment of greywater. The organic pollutants and pathogen can be removed successfully, therefore the treated water can be used safely for irrigation, fishery, or out-door uses. These materials are easily found and locally available. The CWs system offers an economic benefit for householders since there is no or less energy required for the operation of the system. In addition, the treated water can replace a part of the fresh water need supplied from the piped distribution system, and be potential to protect surface and ground water resources from pollutants. Moreover, the use of macrophyte plants creates a green space in a single house yard or green public views for neighborhood. The systems applied as decentralized wastewater systems are suitable for developing countries where the potential health benefits from pathogen removal are considerable. Hence, the CWs systems would be preferable compared to the high cost conventional wastewater treatment systems.

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