Removal of pollutants from wastewater using tropical constructed wetland

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Abstract. A constructed wetland is considered as a cheap and sustainable alternative for wastewater treatment. The aim of this study is to find the most suitable plants or combination of plants along with the substrate for a horizontal sub-surface flow constructed wetland in Brunei Darussalam. The plants performance regarding removal efficiency of E. coli (EC), Total Coliform (TC), Total Nitrogen (TN), Total Oil and Grease (TOG) and Total Petroleum Hydrocarbon (TPH) were determined during this study. Twelve units of cell A (A1, A3, and A4) made of pixel glass and four units of cell B made of concrete are filled with 0.4 m depth of substrate. Each of cell of A1, A3 and A4 is planted with any of these local plants such as Pandan (Pandanus amaryllifolius)/Nipah (Nypa fruticans) or Lalang (Imperata Cylindrica). The cells in B are planted with all three plants but with different ratio of plant density. Each cell’s performance was analysed based on removal efficiency of EC and TC, TN, TOG and TPH. The study concluded that using sand as substrate was found to be most efficient for removing EC and TC consistently and effectively when planted with Nipah, Pandan and Lalang at a ratio of 1:1:1.

1. Introduction

Wetland is a land area that is wet during certain part or all throughout the year because of their location in the landscape. Historically, wetlands are called swamps, marshes, bogs, fens, or sloughs, depending on existing plant and water conditions, and on the geographic setting. A constructed wetland (CW) is divided into four components; they are macrophyte, substrates, water and living organism. Macrophyte is a plant which grows in a wetland. These plants absorb nutrients from the wastewater while filtering the water from suspended solids. It also acts as a vessel for microorganisms to grow that is important in providing biological treatment of wastewater. CW consists of substrate which is a medium for wastewater flows. Typically, the type of substrates used is gravel. There are several factors which contribute to efficient substrates. The amount of organic matter present in the substrates must be within 15% to 20% [1]. The organic matter provides a source of carbon used for microbial activity. This helps create an anoxic condition due to the high oxygen demand, favourable for de-nitrification process. It is also important to choose a substrate which has a suitable permeability,
porosity, bulk density and resistance to compaction or erosion. Furthermore, the pH level of the substrate must be within the range of 6.6 to 7.5 to allow the survival of the vegetation and the microorganism present in the substrate which will help in the treatment process. However, the ultimate factor which contributes to the use of a substrate is the cost and availability of the substrate materials.

In the past decades, the use of CW has been increasing in the developing countries due to high treatment efficiency, low maintenance and operation cost, and its ecological and recreational benefits [2]. A CW is considered as a cheap and sustainable alternative for wastewater treatment, it mimics the natural wetland. Hence, the CW is a good alternative to effluent treatment in addition to the final treatment process or a replacement of the conventional wastewater treatment facility. In this study, a horizontal sub-surface flow (HSSF) wetland was constructed for treating ground washing from markets, restaurants, and sewer leakage. HSSF CW is selected because it is cheaper (364 US$/capital cost and 0.0381 US$/m³ operation cost.) as compared to vertical sub-surface flow (VSSF) (521 US$/capital cost and 0.137 US$/m³ operation cost) [5]. The aim of this study is to design the most suitable plants or combination plants that are locally available along with the substrate for a constructed wetland in Brunei Darussalam. The study compares the performance of three different types of plant that grows in Brunei Darussalam. These plants are Pandan (Pandanus amaryllifolius), Nipah (Nypa fruticans) and Lalang (Imperata Cylindrica).

2. Methodology
In this research a HSSF CW has been designed to determine the types of plants and substrate with various combinations for removal of EC, TC, TN, TOG and TPH. The CW is located in Batu Satu, Jalan Raja Isteri Pengiran Anak Saleha (4° 53’3.25” N, 114° 55’51.04” E) near to Kolej Universiti Perguruan Ugama Seri Begawan (KUPUSB) as shown in figure 1. The treatment compound is between 40 m in length and 15 m in width. The wastewater comprises of washing from market, restaurants and sewer leakage and was collected from the nearby drains using a pump and stored in six tanks connected to the cell as shown in figure 2. The influent characteristics for wastewater are shown in table 1.

![Figure 1. Location of treatment plant.]

For this study, two types of cells were selected, cell A and cell B. The sizing of the cell (unit) is based on the ‘Rule of thumb’, with the minimum ratio of 1:3. There are 16 units of cell A which is
made of plexiglass to allow the viewing of the substrate and root development of the plants. The cell has a size of $1.5 \times 0.5 \times 0.45$ m that is filled with 0.4 m depth of substrate. The 4 units of cell B are made up of concrete and have a size of $2.4 \times 0.8 \times 0.5$ m and it is filled with 0.4 m depth of substrate. The cell is supplied with wastewater at one end of the tank through a 36 mm polyvinyl chloride (PVC) pipe. It is then drained down the 1% slope to the effluent pipe [6]. The influent and effluent flow rate is controlled by adjusting the valves at the inlet and outlet pipe.

Figure 2. Layout of the CW cells and tanks.

Table 1. Influent characteristic.

| Parameter          | Influent          |
|--------------------|-------------------|
| BOD                | 20.28-10.80 mg/L  |
| COD                | 130-194 mg/L      |
| E. coli            | 200-3600          |
| Total Coliform     | 2500-12000        |
| pH Level           | 6.50-7.06         |
| Total Nitrogen     | 2.19-3.07 mg/L    |
| TOG                | 10-33 mg/L        |
| TPH                | 9-25 mg/L         |

There are three types of substrate used for the cells, these substrates are (i) sand, (ii) 1-5 mm gravel and (iii) a mixture of coconut peat, 1-5 mm gravel, and sand. Sand and gravel are commonly used in CW design as they are inexpensive, locally available, and efficient in filtering pollutants. Meanwhile, the use of organic and traditional substrates is based on trial and error where the coconut peat is expected to act as a source of carbon that is important for the growth of the plants and improve the
treatment performance of the macrophytes [7]. For this study, Cell A1 is filled with Sand, A2 is left empty (not being used for the experiment), A3 is filled with 1-5 mm Gravel and A4 is filled with coconut peat, sand and gravel (table 2). The substrate mixture of gravel, sand and coconut peat are used in cell A4, B1, B2, B3 and B4 as shown in table 2 and table 3.

Plants play an important role in determining the success of constructed wetland system as it helps to enhance the process of nutrients removal. Various studies have been conducted around the world to demonstrate higher removal efficiency of nutrients in CW system [8]. There are three types of plant species used in this project, two of them are local plants named Pandan and Nipah and a common plant called Lalang as shown in table 2.

Table 2: Plant species in cell A.

| Cell          | Plant Species                        |
|---------------|--------------------------------------|
| A1 (Gravel)   | Control (Un-vegetated)               |
|               | Pandan (*Pandanus amaryllifolius*)   |
|               | Lalang (*Imperata Cylindrica*)       |
|               | Nipah (*Nypa fruticans*)             |
| A3 (Sand)     | Control (Un-vegetated)               |
|               | Pandan (*Pandanus amaryllifolius*)   |
|               | Lalang (*Imperata Cylindrica*)       |
|               | Nipah (*Nypa fruticans*)             |
| A4 (Coconut peat, Sand and Gravel) | Control (Un-vegetated)               |
|               | Pandan (*Pandanus amaryllifolius*)   |
|               | Lalang (*Imperata Cylindrica*)       |
|               | Nipah (*Nypa fruticans*)             |

Pandan is a local plant that is commonly used for making traditional food in Brunei Darussalam and it can be easily found in the traditional markets. In addition, Nipah is a type of plant commonly found in the riverbanks and coastal zones of Brunei Darussalam. Nipah plant has high tolerance to survive in flooded area which is suitable for this study. Lalang is the most used plant species for CW and can grow easily without any proper care. Each of Cell A1, A3 and A4 was planted with one type of plant species and Cell B1, B2, B3 and B4 was planted with all three plants with varying ratio of plant density (table 3). The diagram of each cells and the plants are attached in figure 3.

Table 3. Design of plant combination for cell B.

| Substrate in each Cell B (Coconut peat, 1-5 mm gravel, and sand) | Ratio of plant density (Nipah: Pandan: Lalang) |
|------------------------------------------------------------------|-----------------------------------------------|
| B1                                                               | 1: 1: 3.5                                      |
| B2                                                               | 1: 3.5: 1                                      |
| B3                                                               | 3.5: 1: 1                                      |
| B4                                                               | 1: 1: 1                                       |

There was two Surface Hydraulic Load (SHL) designed for this study, the SHL are 1.0, and 0.5 m³/m² per day. SHL is the amount of water flowing through a plan area in a specific time. The SHL of the cells is set up by adjusting the valves of the inlet and outlet pipes. The system is set at a chosen SHL for 3 weeks and at least 3 samples were taken from each SHL.
The water samples are collected from the outlet of each cell, including the inlet into 0.8-liter bottles, and stored in 4°C before it is tested for different water quality parameters. In addition, the water temperature and pH level are recorded on site during the time of collection. The collected samples were tested according to the standard procedure. The parameters tested for this study is EC and TC used as indicator bacteria by health authorities to detect contaminated water. Typically, EC constitutes about 20 to 30 percent of the TC found in raw and treated domestic wastewater. TN is determined through three of its common forms which are Ammonia, Nitrate and Nitrite. TOG and TPH are determined using the TOG/TPH analyser. The samples are tested for EC, TC, pH, TN (Ammonia, Nitrate and Nitrite), TOG and TPH. The removal efficiency of the cells is then calculated using the formula shown in equation (1).

$$\text{Removal (\%)} = \frac{C_i - C_e}{C_i} \times 100$$  \hspace{1cm} (1)

Where $C_i$ is the influent concentration of the sample and $C_e$ is effluent concentration of the sample, both in mg/L.

3. Results and discussions

The results obtained have shown that the EC removed by macrophytes planted individually ranges from 14% to 100% and has a TC removal of 13% to 100%. Although, some cells require time to achieve treatment performance it is observed that, in the most cases, it takes 5 days. It is observed that for cell B4 (1:1:1) the removal efficiency of EC and TC is consistently higher in comparison to other combination of plants. An increase in HRT will increase the quality of the effluent as the increased time exposure results into more physical and bio-chemical treatment to the wastewater [10]. Since the HRT is inversely related to the SHL, a decrease in SHL will produce an increase in removal efficiency. This can be seen in the removal efficiency in the cells where an increase in SHL from 0.5 to 1.0 m³/m³ per day has caused a decrease in removal percentage varying from 1% (A4-Pandan) to 49% (A4-Nipah) for EC removal. There is also a decrease in TC removal ranging from 2% (A1-Pandan) to 34% (A4-Nipah). However, some cells are not affected by the change in SHL which can be seen in the unvegetated cell in its removal efficiency of EC. This may be due to the several factors, such as the removal of TC and EC from UV radiation predation and bacteria naturally died off [11].

The results have shown that all cell A3 (Sand) have the highest average removal treatment of EC and TC at 100% efficiency as shown in figure 4 and figure 5 respectively. The EC and TC removal in cell A1 (Gravel) is the highest when planted in Pandan (100% and 99%) followed by Lalang (98% and...
94%), Nipah (95% and 89%) and Control (88% and 82%). The cells A4 that are filled with coconut peat, sand and gravel have lower removal efficiency for Pandan, Lalang and Nipah but slightly higher efficiency without any vegetation. There are several factors affecting the removal of microorganism which involves physical, chemical, and biological process. The physical aspects involve the process of sedimentation, filtration, and degradation of microorganisms due to UV radiations. The chemical aspects involve the oxidation of the organic matter, reaction between the enzymes from the plants and microorganism.

On the other hand, cell B has EC removal efficiency from 82% to 86% and TC removal efficiency from 83% to 88%. The EC (86%) and TC (88%) removal is the highest when the density of plants is in a ratio of 1:1:1 which is in cell B4. The lowest removal efficiency of EC (82%) belongs to cell B2 where the cell has the highest density of Pandan and the plants are planted in a ratio of 1:3.5:1. In addition, cell B3 has the lowest TC (79%) removal where it is planted with a high density of Nipah with a ratio of 3.5:1:1. This maybe is due to the survival competition among the plants as the roof of one plant species prohibits the growth of other plants.

It is important to monitor the pH value of the soil to achieve an efficient removal performance. It is preferable to keep the pH level within 6 to 8 to achieve an optimized process of de-nitrification [1]. Based on the data obtained, the pH value of the inlet ranges from 6.50 to 7.06 and has an average of 6.72 which is considered very slightly acidic. For the cells that are vegetated with individual plant species, the pH level varies from 6.96 to 8.10 and has an average of 7.53. The un-vegetated cells have a pH range of 7.32 to 7.97 with an average of 7.67. The pH level of cell B1, B2, B3 and B4 has an overall range of 7.26 to 8.09 and has an average value of 7.68. From this analysis, the treatment process will increase the pH level of the acidic influent into an alkaline condition and it is within the preferable limit.

Based from the results, when SHL is set as 0.5 m$^3$/m$^2$ the removal efficiency of TN is higher in cells with Pandan and Nipah vegetation. The highest removal efficiency for TN is at cell A4-Pandan with 90% and followed by A4-Nipah with 84%. This indicates that substrate of cell A4 (which is the combination of coconut peat and coarse aggregate) are relatively good in contributing to the removal of TN in comparison to other substrates. The result is very encouraging as compared to other studies done using HSFW for removal of TN was 10-36% [12]. Similar results are obtained when the CW units are set up with SHL of 1.0 m$^3$/m$^2$, where cell A4-Pandan and A4-Nipah are still two of the cells with highest removal efficiency of 74% and 50% respectively. Increase in the value of SHL means that the amount of wastewater flow into the constructed wetland per unit area in a day is increased, therefore less time for the removal of TN to take place. As a result, the value of TN removal efficiency is much lower compared to SHL of 0.5 m$^3$/m$^2$. 


Figure 4. Average removal efficiency of *E. coli* in cell A.

Figure 5. Average removal efficiency of Total Coliform in cell A.

The highest removal efficiency of TN is Cell B3 is 60% which consists of Nipah, Pandan and Lalang planted at a ratio of 3.5:1:1 respectively. This experimental study has demonstrated that Nipah remarkably performed well in removing TN. TN is removed as wetland vegetation consumes ammonia and nitrate by converting inorganic matter (nitrogen) into organic forms by assisting build ups of cells and tissue of the plant [5]. Nipah and Pandan have larger surface area for microbial activities due to greater size and number of roots and therefore, performs better in the removal of TN compared to Lalang. The study finds that cells with vegetation have the higher removal efficiency compared to cells with no vegetation (control). This proves that the vegetation plays an important role in removing pollutants and increases the pollutant removal efficiency in CW system. It is done by converting dissolved carbon into foods to promote the growth of microbial activities during photosynthesis. The TOG removal in the constructed wetland ranged from 74% to 90% when SHL is set to 0.5 m$^3$/m$^2$ and 43% to 72% when SHL is equal to 1.0 m$^3$/m$^2$. The removal efficiency for TPH ranged from 61% to 86% when SHL equal to 0.5 m$^3$/m$^2$ and 51% to 78% when SHL set to 1.0 m$^3$/m$^2$. The highest average removal efficiency of TOG and TPH is at Cell A3-Nipah and lowest at Cell A4-Control. The substrate
helps in trapping TOG and TPH from the wastewater and the vegetation helps in absorbing them. Substrate like sand has higher removal efficiency for TOG and TPH as sands having relatively smaller particles allows wastewater to pass slowly and thereby giving more time for the pollutants to be trapped and absorbed. A combination of coarse aggregate and coconut peat (Cell A4) has the lowest removal efficiency for both TOG and TPH as having larger pores allow wastewater to pass quickly and giving less time for pollutants to be trapped and absorbed.

4. Conclusion
Sand when planted with Pandan and Lalang is very efficient in removal of EC and TC. Even though, the growth rate in terms of leaf size and density are slower for both Pandan and Lalang in sand. However, the root growth is very extensive in the sand. The EC and TC removal is the highest when planted in Pandan (100% and 99%) followed by Lalang (98% and 94%), Nipah (95% and 89%) and while without plant i.e. under Control (88% and 82%) respectively. The EC (86%) and TC (88%) removal is the highest when the density of plants is in a ratio of 1:1:1 when planted with Pandan, Lalang and Nipah. Based from the result, Pandan are relatively good in the removal of Total Nitrogen, TPH and TOG with highest removal efficiency of 90%, 89% and 84% respectively. Cell A3 (combination of coconut peat and coarse aggregate) are good in TN removal with highest removal efficiency of 90% and on the other hand, sand is relatively good in the removal of TOG and TPH with highest removal efficiency of 90% and 86% respectively. As a result, it can be concluded that the best design of CW in terms of TN, TOG and TPH removal would be cells with combination of sand and fine aggregate as the substrate planted with Pandan.

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