Biofiltration System for Stormwater Treatment in Tropical Environment

A thesis submitted in fulfillment of the requirement for the degree of Doctor of Philosophy in Civil Engineering

by

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Andreas Aditya Hermawan

February 2018

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Abstract

Biofiltration systems are landscape depressions or shallow basins that have been used to slow down and treat the stormwater on-site. Biofiltration systems are considered as one of the important components of a sustainable drainage system and generally consist of two components: a sand-dominant filtration media and the vegetation. The efficiency of biofiltration systems is normally assessed by two key parameters namely infiltration rate and pollutants removal efficiency. To date, several studies have been done on development and maintenance of such systems; however, few have been carried out to understand design requirement of such systems under tropical climates with annual rainfall ≈2500 mm. To address this issue, a soil column experimental set up was considered to characterize the key components of designing biofiltration systems under tropical conditions of Malaysia. In this study, the first aim is to identify a filter media that can remove heavy metals efficiently from stormwater while its infiltration rate is higher than 100 mm/hr. For this, non-vegetated soil columns with 160 mm diameter were set up with sand-based media and four fine-grained materials (fly ash, zeolite, Hals – Matauri Bay, Hals – UltraHalloPure). The removal of heavy metal ions such as Zn(II), Pb(II), Ni(II), Fe(III), Mn(II), and Cu(II) were tested for the infiltrated stormwater to the system. The results showed that generally 2 – 5% of fine-grained materials would lower the infiltration rate value by 9.0 – 75.5%. The heavy metal ions removal efficiency was able to achieve >80% for Zn(II), Pb(II), Ni(II), and Cu(II). The second objective of this study was focused on identifying proper local plants which can be used in biofiltration system. For this, soil columns with 200 mm diameter were used to provide more space for plants growth. Moreover, a submerged zone was provided in the system to allow plants to survive during dry periods. In addition to heavy metals removal, the capability of the system for nutrients (total nitrogen and total phosphorus) removal was assessed. Results showed that not only plants can remove nutrients from stormwater (up to 38% of TN removal and 90% of TP removal), but also capable of maintaining/improving the infiltration rate. This was evident when vegetated columns were compared with non-vegetated ones. Among ten selected native plants, *Cymbopogon nardus*, *Hibiscus rosa-sinensis*, and *Iris pseudacorus* could not survive the monitoring stage. *Pedilanthus tithymaloides*, *Heliconia psittacorum*, and

Hymenocallis speciosa were studied under non-seasonal study and found to be sensitive towards pollutants load from the incoming stormwater which eventually dried up. Seasonal study was conducted on *Cordyline fruticosa, Graptophyllum pictum*, *Cyperus alternifolius*, and *Bambusoideae,* and it was found that the plants could survive well even after a long dry period of 21 days. In general, the infiltration rates obtained on the four plants were all above 400 mm/hr, which was higher than the recommended values by guidelines. Moreover, the treated water concentration managed to satisfy the requirements for class IV Malaysia standard discharge water quality for irrigation purpose.

Publications During Enrolment

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Hermawan, A. A., Rahman, M. I. B., Talei, A., Teo, F. Y. 2017. Impact of submerged zone depth on stormwater pollutants removal in tropical biofiltration systems. In: 37th IAHR World Congress, 13-18 August 2017, Kuala Lumpur, Malaysia.

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Keywords

Biofiltration system;

Biofilter;

Tropical;

Stormwater treatment;

Stormwater management;

Filter media;

Fly ash;

Zeolite;

Halloysite nanotubes;

Heavy metals;

Nutrients;

Submerged zone;

Vegetation;

Infiltration rate;

Seasonal;

List of Abbreviation

LID	Low Impact Development
WSUD	Water Sensitive Urban Design
FAWB	Facility for Advancing Water Biofiltration
TSS	Total Suspended Solid
BPP	Best Planning Practice
BMP	Best Management Practice
SuDS	Sustainable Drainage System
TN	Total Nitrogen
TP	Total Phosphorus
DID	Department of Irrigation and Drainage
MSMA	Manual Saliran Mesra Alam
MY	Malaysia
US	United States
UK	United Kingdom
Fe	Iron
Cu	Copper
Mn	Manganese
Ni	Nickel
Pb	Lead
Zn	Zinc
Cd	Cadmium
Cr	Chromium
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
NO_2	Nitrite
NO_3	Nitrate
TDP	Total Dissolved Phosphorus
FRP	Filterable Reactive Phosphorus
PVC	Polyvinyl Chloride

FA	Fly Ash
Z	Zeolite
MB	Matauri Bay
UHP	UltraHalloPure
XRD	X-Ray Diffraction
FE-SEM	Field Emission Scanning Electron Microscopy
XRF	X-Ray Fluorescence
ASTM	American Society for Testing and Materials
ICP-OES	Inductively Coupled Plasma – Optical Emission Spectrometry
UV-vis	Ultra Violet – visible
ARI	Average Recurrence Interval
SEM	Scanning Electron Microscopy
NOM	Natural Organic Matter
IR	Infiltration Rate Score
PR	Pollutant Removal Score
NEC	Normalized Effluent Concentration
CN	*Cymbopogon nardus*
HR	*Hibiscus rosa-sinensis*
IP	*Iris pseudacorus*
PT	*Pedilanthus tithymaloides*
HP	*Heliconia psittacorum*
HS	*Hymenocallis speciosa*
CF	*Cordyline fruticosa*
GP	*Graptophyllum pictum*
CA	*Cyperus alternifolius*
BE	*Bambusoideae*

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CHAPTER 1
INTRODUCTION

Stormwater quality and quantity management in urban areas has been one of the major concerns as by increasing rate of urbanization stormwater quantity has increased while its quality has been significantly deteriorated. This has made the urban stormwater treatment as one of the major research topics in many of developing and developed countries since 1965 (Brown and Clarke, 2007). Since then, the development of stormwater management facilities has gone through several rounds of improvement. By changing the perception of managing rainwater as nuisance that must be got rid of to a usable resource, several facilities have been developed and practiced promoting infiltration of rainwater to soil, treat it on-site, and link it to the natural water resources. These Low Impact Development (LID) technologies are mainly focused on integrating urban water management with sustainability requirements (e.g. water conservation, environmental protection, etc.) (Hatt et al., 2009c). Wetlands, detention ponds, green roofs, and biofiltration systems are some good examples of such facilities. Among them, biofiltration systems are found to be successful in removing various pollutants including heavy metals, nutrients, and bacteria from stormwater through their layered filter media. Moreover, biofiltration systems are capable of reducing both runoff peak and volume when they are integrated into the urban water system. To date, several philosophical design approaches are introduced for such facilities in developed countries including United States, United Kingdom, and Australia. Sustainable Drainage System (SuDS) and Water Sensitive Urban Design (WSUD) are examples of the philosophical approaches in urban planning and design which aims to minimize the hydrological impacts of urban development on the surrounding environment (Lloyd et al., 2002). Using WSUD, an adoption guidelines for Stormwater biofiltration systems is developed in Australia by Facility for Advancing Water Biofiltration (FAWB, 2009) which has been widely practiced in Australia and other countries such as Israel, Singapore, etc.

Biofiltration systems consist of two main components: a sand-based filter media and vegetations. The main contribution of filter media is heavy metals and suspended solids removal while plants mainly contribute in nutrient removal. In general, the percolated stormwater to the biofiltration system will get treated by a number of physical, chemical, and biological processes (Sun and Davis, 2007). To date, several studies on successful removal of heavy metals and total suspended solids (TSS) by biofiltration systems have been reported in literature (Davis et al., 2003; Pitcher et al., 2004; Dietz, 2007; Sun and Davis, 2007; Hatt et al., 2008; Blecken et al., 2009b; Reddy et al., 2014b; Strecker et al., 2017; Al-Ameri et al., 2018). These studies have shown that relatively high percentage of concentration reduction can be achieved by soil media alone. Usage of some fine grain materials such as fly ash has been found to improve the performance of heavy metal removal; however, such fine grain materials generally decrease the infiltration rate of the system significantly (Zhang, 2006; Li et al., 2014). Besides that, vegetations in biofiltration system studies have been reported to be effective in removing nutrients pollutants due to plants uptake (Davis et al., 2006; Fletcher et al., 2007b; Henderson et al., 2007; Hsieh et al., 2007a; Hsieh et al., 2007b; Bratieres et al., 2008; Read et al., 2008; Payne et al., 2018). These studies show the performance of various plants species for nutrients removal in biofiltration system. Few plants characteristics including root growth pattern and plants' size play a role in the overall performance of biofiltration system.

Although biofiltration systems showed promising performance in stormwater management in many countries (such as U.S. and Australia), they are not much dominant in South East Asia in which many developing countries are located. One of the major issues in that region beside the fast rate of urbanization, is the tropical climate. Very few studies have evaluated the functionality of biofiltration systems under tropical conditions with high rainfall intensity, hot weather, and extreme humidity. Moreover, the performance of tropical plants in biofiltration systems are not also well-studied

In the present study, laboratory-scale soil column biofiltration experimental set ups were prepared using different local soil materials and plants to be assessed under tropical weather condition. Performance of the systems for infiltration rate and pollutants removal (heavy metals and nutrients) were evaluated. The two typical tropical seasons known as monsoon and non-monsoon seasons were simulated in the lab by imposing wet and dry conditions in lab, respectively. Malaysia discharge water quality standard (DOE, 2006) was used as a basis to compare and assess the quality of the system's effluent.

The present thesis is organized into 8 chapters. Chapter 1 is an introduction on stormwater management in urban areas in which discussions are made on the current emerging issues in this field of study. Chapter 2 presents a profound literature review on biofiltration systems where the structure of biofiltration system is explained and the past research studies on the functionality and performance of such system in stormwater treatment and management are reviewed. Chapter 3 presents the scope, aims and objectives of this study. Chapter 4 presents the methodology of this research including the experimental set up, analytical test used, and procedure of the experimental study. Chapter 5 discusses the results of non-vegetated columns study where the impact of adding few fine-grained materials on system performance has been studied. Chapter 6 presents the results of vegetated columns study where the performance of different plants used in biofiltration system under non-seasonal and seasonal conditions is discussed. In Chapter 7, the functionality of biofiltration system for different submerged zone heights and for the clogging potential is discussed. Chapter 8 concludes the findings of this study.

CHAPTER 2
LITERATURE REVIEW

2.1 Stormwater Treatment

Stormwater is defined as surface runoff generated by rainfall which enters natural drainage systems like streams and rivers by overland flow or through storm drains (Adams and Dove, 1984). Stormwater carries pollutants from many source points such as roads and roofs. Heavy metals contributing in stormwater pollution are sourced from automobiles fluid leaks and tires, paintings and metal components of buildings, as well as atmospheric deposition (Davis et al., 2003). Beside heavy metals, presence of excessive nutrients in stormwater has created environmental concerns. Excess of nutrients including nitrogen and phosphorus is a result of artificial fertilizers and concentrated sewage (Hunt et al., 2006). Therefore, stormwater management becomes a necessity and has been one of the major research topics in many developed and developing countries. Conventional stormwater management such as implementation of curb, gutter, and piping systems has been used to discharge stormwater runoff to the nearest receiving water (Houle et al., 2013). In such conventional practice, aim is to remove stormwater from a site as fast as possible to mitigate on-site flooding. However, some researchers have proven that such practice is devastating for downstream waters due to the increased frequency and magnitude of discharge, alteration of stream channel morphology, and increased of groundwater pollutions (Jennings and Jarnagin, 2002). The afore-mentioned drawbacks of conventional stormwater management are mainly due to the efficient transfer of runoff and end pipe treatment. McCarthy (2008) stated that the key to effective management of stormwater runoff is to reduce the amount of stormwater generated in the first place by maintaining and working with the hydrology of a site and managing stormwater at the source. Due to the increased rate of urbanization especially in developing countries, conventional stormwater management is no longer sustainable.

To date, stormwater treatment has gone through several improvements. By changing the perception of managing stormwater runoff as nuisance that must be got rid of to a utilizable resource, several solutions have been developed to capture stormwater and improve its quality while returning it to the water resources. Water Sensitive Urban Design (WSUD) as a philosophical approach in urban planning and design, aims to minimize the hydrological impacts of urban development on the surrounding environment and has been practiced in many countries including Australia starting in 1990s (Lloyd et al., 2002; Ahammed, 2017). The two types of practices that promote stormwater management structure in a long-term basis are called Best Planning Practices (BPP) and Best Management Practice (BMP). They both can be applied for land development, redevelopment sites in build-up region, as well as retrofitting of urban catchment. Besides WSUD, Low Impact Development (LID) approaches design with nature to minimize the cost of stormwater management (Dietz, 2007). The implementation of LID was officially sanctioned in US and Canada in 2007 and 2010, respectively. In UK, Sustainable Drainage Systems (SuDS) was established in 1997 to define stormwater management technology. Similar with the principles in LID, SUDS are an arrangement of technologies, techniques, and systems that work together to form a management chain (Fletcher et al., 2015).

Malaysia as one of the tropical countries experience higher rainfall intensity (see Figure 1), thus naturally produces higher volume of stormwater runoff (The World Bank Group, 2018). The average annual rainfall in Malaysia was ≈2500 mm with 60-93% of reliative humidity (Islam et al., 2017), while in Australia the annual rainfall was <600 mm with 18.2-95.1% humidity during summer (Lam and Lau, 2018). Despite the different environment condition (tropical and temperate), the approaches to the design procedure, for both methods and techniques employed in Malaysia have not been upgraded although few integrated urban design such as WSUD, LID, and SuDS have been practiced widely overseas (Zakaria et al., 2004). With the increasing of urbanization, flash floods occur more frequently due to the increase in surface runoff. Moreover, sedimentation and pollution in river systems are the other two major concerns. Table 1 shows the typical heavy metals and nutrients concentration for urban stormwater runoff with different land use in Malaysia and United States. It can be seen that stormwater runoff in Malaysia generally has higher pollutants concentration and may potentially harm the environment. Another stormwater quality study was conducted by Yusop et al. (2005) in Pandan catchment in Johor, Malaysia with catchment area of 17.14 km^2. The land use consisted of 27.3% agricultural, 30.3% residential, 6.4% commercial, 8.1% industrial, and 27.9% open space. In comparison, Duncan (1999) and Taylor et al. (2005) summarized the data of world average stormwater pollutant concentration. Few pollutants in Malaysia catchment such as Cu, TN, and TP showed significantly higher concentration than world average data, thus could be a concern. The summary of the comparison are shown in Table 2.

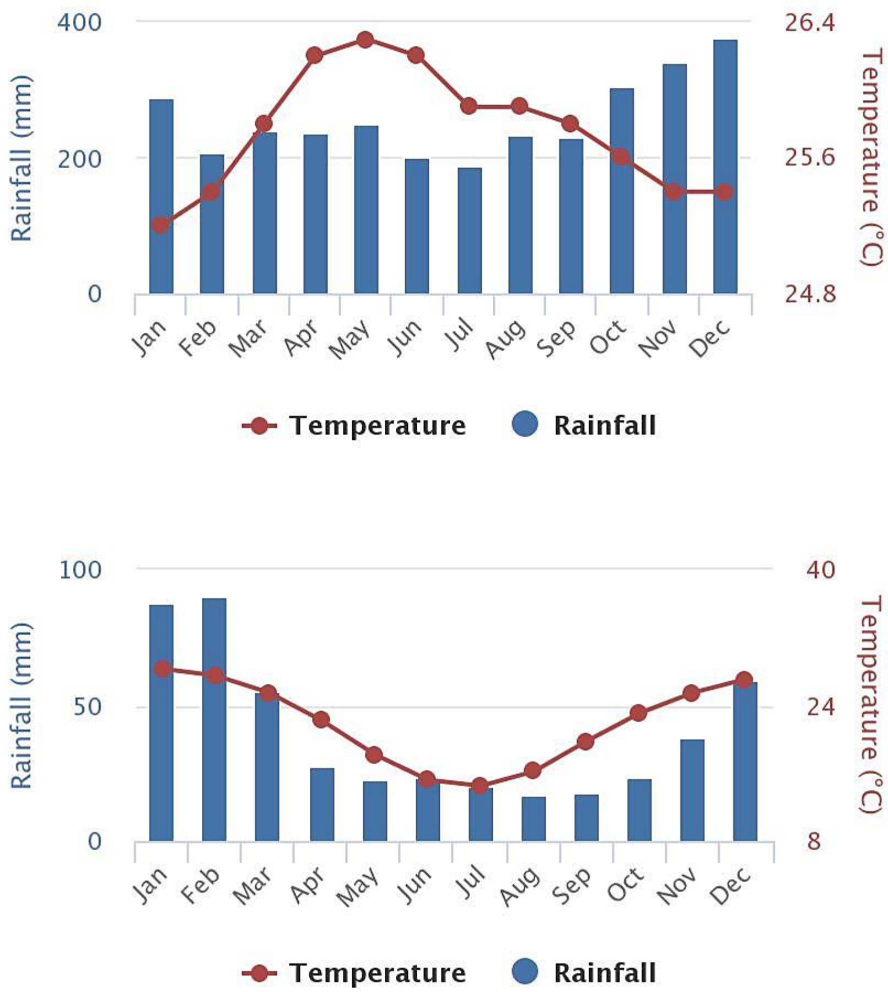


Figure 1: Average monthly rainfall and temperature for Malaysia (top) and Australia (bottom) from 1991-2015 (The World Bank Group, 2018).

To overcome this problem, Department of Irrigation and Drainage (DID) Malaysia introduces Stormwater Management Manual for Malaysia (known as MSMA) starting from 2001. MSMA uses the application of BMP to improve the stormwater quality and quantity management to a certain standard so it can be released into natural water bodies such as rivers, lakes, oceans, or groundwater. The design of water quantity are based on the Average Recurrence Interval (ARI) and peak discharge estimation for the corresponding water body (MSMA, 2012). For water quality management in Malaysia, the targeted stormwater quality after treatment is classified based on Malaysia's discharge water quality standards. There are 7 classifications of water, and the target for stormwater quality after treatment by BMP is either class IIB or IV where the latter is for irrigation and the former is for recreational purposes. Table 3 shows the target concentration of treated stormwater for both class IIB and IV.

Table 1: Typical stormwater pollutants concentration based on urban land use (Pitt et al., 2004; MSMA, 2012).

Pollutants	**Unit**	**Residential**		**Commercial**		**Industrial**		**Freeways**	
		MY	**US**	**MY**	**US**	**MY**	**US**	**MY**	**US**
Zn	mg/L	0.19	0.07	0.34	0.15	0.43	0.21	0.21	0.20
Pb	µg/L	6.00	12.00	22.00	18.00	12.00	25.00	20.00	25.00
Cu	µg/L	28.00	12.00	37.00	17.00	42.00	22.00	28.00	34.70
Cr	µg/L	4.00	4.60	32.00	6.00	31.00	14.00	11.00	8.30
Ni	µg/L	10.00	5.40	17.00	7.00	30.00	16.00	15.00	9.00
Cd	µg/L	6.00	0.50	26.00	0.89	5.00	2.00	10.00	1.00
TN	mg/L	4.21	2.00	4.84	2.20	5.00	2.13	2.25	2.28
TP	mg/L	0.34	0.30	0.32	0.22	0.49	0.26	0.16	0.25

*MY = Malaysia

*US = United States

Table 2: Comparison of urban stormwater pollutant concentration (ppm) between Pandan catchment, Johor and world average value. (Duncan, 1999; Taylor et al., 2005; Yusop et al., 2005)

Pollutants	Pandan catchment	World Average
Fe	0.86	-
Cu	0.15	0.05
Mn	0.04	0.23
Ni	0.01	0.03
Pb	0.01	0.14
Zn	0.16	0.25
TN	4.32	2.60
TP	1.12	0.32

There are several technologies that have been thoroughly studied to address the available issues in urban drainage systems. Wetlands, detention ponds, green roofs, and biofiltration systems are examples of such solutions. Wetlands are piece of lands where water covers the soil (or is present either at or near the surface of the soil) throughout the year or for varying periods of time during the year, including during the growing season (Zedler and Kercher, 2005). As one of the most productive ecosystem in the world, wetlands mainly aim to provide great volumes of food such as dead plant leaves and stems to attract many animal species. Generally, wetlands can be thought of as biological supermarkets. Detention pond is one of the most important facility to control stormwater quantity impacts from urban catchment. Detention pond can be constructed as either dry or wet pond, where permanent ponding zone is present only in wet pond. However, to ensure that sufficient flowrate for maintaining pool level is achieved, MSMA (2012) suggested that the total land use needs to be greater than 100000 m^2. Green roof is a roof system which is covered by vegetation and a growing medium (Berndtsson, 2010). The primary benefit of green roof is to mitigate stormwater runoff. On the other hand, biofiltration systems mainly consist of a soil media and vegetation which are built on the ground and target stormwater management for both quality and quantity aspects (Davis et al., 2009).

Table 3: Malaysia water quality standard (DOE, 2006).

Parameter	Unit	Class	
		IIB	IV
TSS	ppm	50	300
pH	-	6-9	5-9
Cu	ppm	0.02	-
Fe	ppm	1	5
Mn	ppm	0.1	0.2
Ni	ppm	0.05	0.2
Zn	ppm	2	5
Cd	ppm	0.01	0.01
Cr	ppm	0.05	0.1
BOD	ppm	3	12
COD	ppm	25	100
TP	ppm	0.2	-
NH_3-N	ppm	0.3	2.7
NO_2	ppm	0.4	1
NO_3	ppm	7	5
Fecal coliform	count/100 ml	400	5000

2.2 Biofiltration Systems

2.2.1 Structure of Biofiltration System

Biofiltration systems are landscaped depressions or shallow basins that can slow down and treat stormwater on-site. Biofiltration system is considered as a low-energy treatment technology with the potential to provide both water quality and quantity control (Hatt et al., 2009a). Biofiltration systems consist of a layered soil media with different range of particle sizes which accommodates vegetation on its top surface as shown in Figure 2. In general, soil contributes to sediments and heavy metal ions removal while plants contribute to nutrients removal. To date, several studies have been conducted in both lab and field scales to assess the functionality and performance of such system for different soil media, plant species, and climates (Davis et al., 2003; Dietz and Clausen, 2005; Hsieh and Davis, 2005; Hatt et al., 2008). In this section, the main components of biofiltration system including filter media and plant characteristics are reviewed. Moreover, the findings of the past studies on biofiltration systems are thoroughly reviewed and discussed.

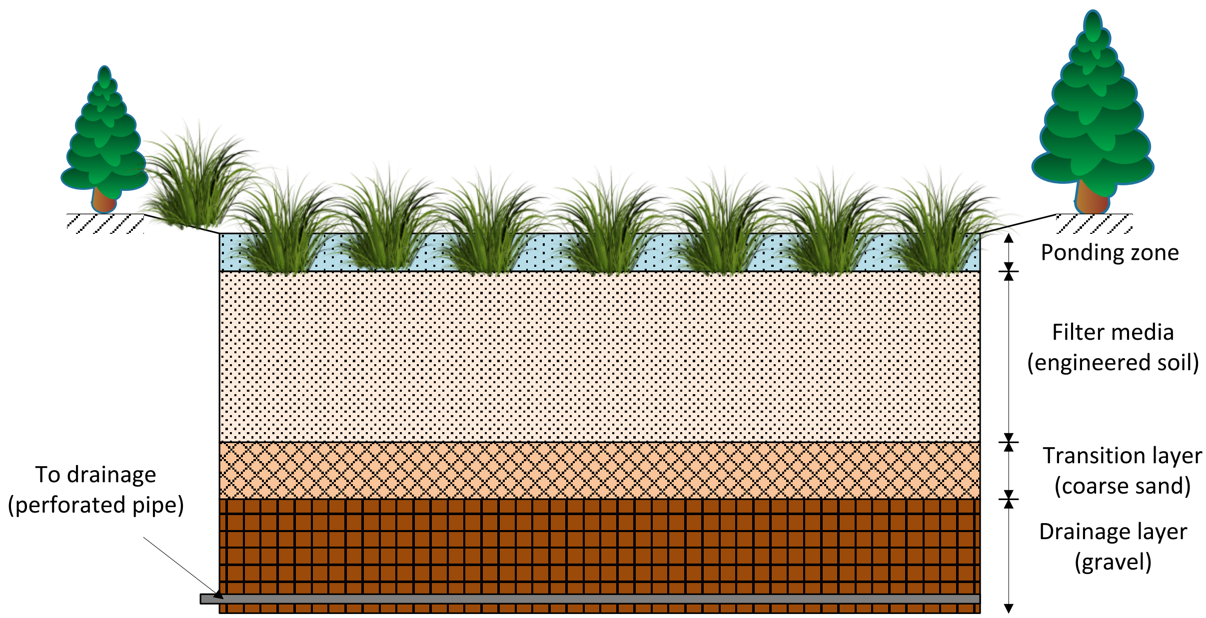


Figure 2: Schematic structure of biofiltration system.

2.2.2 Filter Media of Biofiltration System

Many studies on biofiltration systems have been focused on optimization of the layered filter media structure. The common practice of layered soil media is a three layers media which starts from a drainage layer at the bottom, followed by transition layer and filter media layer in which the roots of the plants penetrate. Drainage layer consists of big aggregates such as gravel, whereas the filter media consists of sand with different particle sizes ranging from very fine sand to very coarse sand (Hsieh and Davis, 2005). In order to prevent the sand from being washed into the drainage layer, an additional layer called transition layer is placed in between. Transition layer has a particle size between drainage and filter media and is working as a bridge between the two layers

(FAWB, 2009). In addition, submerged zone has been proven to be essential for plants survivability especially when a dry season is expected (Blecken et al., 2009a). Submerged zone can be created by raising the outlet level. This provides a water storage capacity inside the biofiltration system. This feature allows the plants to uptake water from this reserved water storage during dry seasons.

Filter media selection is normally linked to the soil properties, catchment characteristics, rainfall properties, and availability of materials in the local market. FAWB (2009) gave a detailed guideline on filter media selection for Australian biofiltration systems. The infiltration rate of 100-300 mm/hr is reported to be required for some of the Australian catchments, while up to 600 mm/hr values are recommended for tropical and sub-tropical areas. Although using slightly higher infiltration rate values than the ones recommended by FAWB may hardly have an impact on pollutant removal efficiency, it is not recommended due to the likely impact of fast drainage on vegetation growth and survivability. In fact, the infiltration rate value recommended MSMA (2012) for tropical climates should not be higher than 200 mm/hr to ensure that the engineered soil media can hold enough soil moisture for the growth of vegetation. However, this case is mainly applicable for biofilters without the installation of submerged zone. It is known that there is always a tradeoff between using small and big soil particle size as small particles support better pollutant removal while bigger particles provide higher infiltration rate. In general, using a small portion (2-3%) of fine particles such as mulch, fly ash, etc. has been found to be effective in enhancing pollutant removal (Hsieh and Davis, 2005; Zhang, 2006). However, to maintain the required infiltration rate between 100-600 mm/hr (FAWB, 2009), using high percentage of fine material is not recommended. Table 4 shows the weight distribution of different particle size suggested by FAWB (2009) to be used in filter media. Few studies on the lifespan of biofiltration system have been conducted. The lifespan of the biofiltration system is based on few criteria such as clogging and the filter media performance. Dechesne et al. (2005) concluded that the typical biofiltration system could stay for 10-21 years until the infiltrated water pollutant concentration exceeded the level of acceptable limit and clogging could not be avoided. This finding was supported by Hatt et al. (2011) which found that the laboratory scale biofilter columns could perform well for 10-15 years.

To date, several soil compositions have been studied to achieve appropriate soil media for biofiltration system. To improve the pollutant removal performance in the filter media layer, fine-grained materials can be applied as a mixture for specific targeted-pollutant from the stormwater. Although conventional materials such as activated carbon has been known for its ability as sorbent, natural adsorbent has gained popularity over the last few years due to its low-cost and effectiveness in removing pollutants (Malekmohammadi et al., 2016). For example, adding small portion of gardening materials such as perlite and vermiculite to the filter media layer of biofiltration system has been found to improve the nutrient removal of biofiltration system in Australia (Bratieres et al., 2008). In some other studies, mulch and compost have been used to enhance the growth rate of the plants (Davis et al., 2003; Lim et al., 2015).

Table 4: Weight distribution of different soil particle size for a standard filter media of biofiltration system.

Material	Size (mm)	Percentage (%)	
		(FAWB, 2009)	(MSMA, 2012)
Clay &silt	< 0.05	< 3	10-25
Very fine sand	0.05-0.15	5-30	20-25
Fine sand	0.15-0.25	10-30	
Medium to coarse sand	0.25-1.00	40-60	50-60
Coarse sand	1.00-2.00	7-10	-
Fine gravel	2.00-3.40	< 3	-
Organic Materials	-	-	12-20

Other fine-grained materials such as fly ash is one of the promising adsorbent due to its low-cost and excellent removal capabilities for certain metals ions. Fly ash is the byproduct produced from burning pulverized bituminous, hard coals in power station furnaces (Sear, 2001). The furnace typically operates at temperature higher than 1400 ^{o}C to generate steam for electricity production. The fusion of mineral impurities and exhaust gas during combustion process resulting in the production of fly ash. Fly ash commonly consists of 38-52% silicon dioxide (SiO_2), 20-40% aluminium oxide (Al_2O_3), 6-16% iron oxide (Fe_2O_3), and 1.8-10% of calcium oxide (CaO). In average, fly ash has a particle size of < 20 μm. It is considered as fine aggregate material in soil classification and it has been used in several water filtration applications including biofiltration system (Cho et al., 2005; Zhang et al., 2008a; Zhang et al., 2008b) due to its high surface area of 300 – 500 m^2/kg (Yao et al., 2015). Fly ash is commonly used as a mixture with sand-based media for the filter media layer of biofiltration system. The addition of fly ash is expected to improve the water quality by removing extra pollutants such as heavy metal ions and nutrients due to its alkalinity and negative charge characteristic. The pollutants removal process by fly ash was found to be either by precipitation process or electrostatic adsorption (Yao et al., 2015). Although the usage of fly ash as fine-grained materials in biofiltration system seem promising, more than 40% of its production resulting in disposal or landfill (Sear, 2001). Therefore, further investigation to utilize the excess production of fly ash should be conducted.

The other fine material used in the mixture of filter media layer in biofiltration is zeolite. Zeolite is a microporous aluminosilicate mineral usually found in volcanic rocks. Zeolite contains a wide variety of cations such as Na(I), K(I), Ca(II), and Mg(II). Natural zeolite has particle size of < 45 μm and surface area of 2900 m^2/kg (Hor et al., 2016). The high surface area of natural zeolite attracted its use as an adsorbent material. However, zeolite naturally contains some metals such as Ti, Sn, and Zn, thus it is commonly known to be high in impurities. Since impurities in the materials would negatively affect its usage as sorbent, therefore synthetic zeolite has gained its popularity than natural zeolite to achieve certain target as sorbent materials (Pitcher et al., 2004).

Besides fly ash and zeolite, using nano-materials such as carbon nanotubes and nanoclays (e.g. layered silicates such as montmorrilonite or MMT and Kaolin) for water purification have been reported by some researchers (Patel et al., 2006; Yuan and Wu, 2007). Halloysite (Hal) is a member of the kaolin group of clay minerals and typically found in microtubular crystals (Pasbakhsh et al., 2016). Halloysite is an abundant and novel nano-material which can be used in water filtration application (Zhao et al., 2013; Makaremi et al., 2015) due to its unique hollow tubular morphology, its unique chemical structure (SiO_2 at the surface while Al_2O_3 is in the lumen and edges) and high surface area (20-70 m^2/g). Hal has started to attract the attention for decontamination of industrial effluents (Pasbakhsh and Churchman, 2015). Yuan et al. (2015) highlighted the considerable potentials of Hal as a new adsorbent for different applications. Authors elaborated the unique properties of Hal such as their high specific surface area compared with Kaolin group. It was concluded that despite the tubular shape of Hal that promotes adsorption capacity, their interlayer is hardly accessible for ions and molecules. Therefore, it is recommended that the modifications could be needed to improve the Hal's properties such as adsorption capacity (Yuan, 2016). The removal efficiency of Hal is higher than most of the conventional adsorbents. Moreover, after absorption, Hal can be regenerated by burning and reused. However, the application of Hals is yet to be known in biofiltration system.

Overall, the composition of filter media varies depending on the application of the system. Fine materials are found to be beneficial for pollutant removal improvement, however the possibility of leaching and clogging should be considered to optimize the design of biofiltration system.

2.2.3 Plants Characteristic for Biofiltration

Plants play a key role in biofiltration system. The main function of the vegetations is to improve pollutant removal efficiency as well as improving the hydrology performance through preventing clogging by help of roots. Moreover, plants improve the aesthetic value of the system by providing green corridors, provide shades, and enhance the microclimate of their environment. These functionalities of plants can be achieved by combining variety of plants according to the design requirement. The vegetation in biofiltration system is commonly planted in the filter media layer, although the gradual root growth can penetrate to transition layer and drainage layer. In biofiltration system application, few different plant types are commonly used, such as grasses, shrubs, and trees (MSMA, 2012; Monash Water for Liveability Centre, 2014). Grasses are herbaceous type plants with narrow leaves that could assist trapping sediments and act as soil stabilizers. One of the most noticeable properties from grasses is the high tolerance to drought condition. However, in field scale application of biofiltration system, grass families are commonly invasive, thus out-competing other plant types (Monash Water for Liveability Centre, 2014). Besides that, the fine roots of grasses were found to contribute to filter clogging. Shrubs are woody plants with less than 5 m height and many branches without a distinct main stem except at ground level. Since shrubs are commonly taller than grasses, it could provide shade for groundcovers and shorter plants. However, the density of plants need to be considered due to the growth rate of shrubs (Hydro International Stormwater, 2011). It is understood that relatively dense planting is advantageous as long as the available moisture is in balance.

Monash Water for Liveability Centre (2014) suggested few principles for choosing plants in biofiltration system. The ability to withstand temporary inundation, as well as prolonged drought are always the two major concerns in plants selection. To survive well in biofiltration filter media, plants need to be adaptable to fast draining sandy media. In addition, plants' root shape, length, and propagation style should contribute to the hydrologic performance of biofiltration by reducing the potential of clogging. In general, a higher density of plants is desirable; however, it should not drain out the available water storage in a short period of time (in dry season). Moreover, the media used for the biofiltration system should not contain high amount of nutrients as it may promote nutrient leaching. For tropical environment, MSMA (2012) suggested additional consideration for plants selection such as priority towards nativity, urban stressors, avoiding noxious weeds, aesthetic value, as well as traffic and safety when dealing with trees. Based on the plant selection criteria, several vegetations were recommended by the Malaysian guidelines such as *Arundina graminifolia*, *Cyclosorus aridus*, *Ipomoea cairica*, and *Ishaemum muticum*.

Ong et al. (2012) conducted a monitoring study on the first biofiltration system in Singapore throughout the period August 2009 – July 2010. Twelve different plant species were used in the study including *Cyperus alternifolius*, *Typha geniculate*, *Cyathula prostata*, *Neomarica gracilis*, etc. It was found that most of the plants grow fast during one year of monitoring, thus periodic trimming and pruning were required to avoid overly dense of vegetation. Additionally, few plant species such as *Thalia* *geniculata* and *Typha geniculata* required manual watering during prolong drought condition. Another study on tropical environment was conducted by Salih et al. (2017) where three different plants including *Phragmites*, *Ipomoea aquatica*, and *Pistia* were used as biofilter in local sewage treatment plants. Authors concluded that Pistia has the best potential to be used in biofiltration system in comparison with the other two plant species due to its pollutant removal capability.

Read et al. (2008) conducted a comprehensive study on the effect of using different plants species for pollutants removal efficiency in biofiltration system. Authors compared pollutants removal capability of twenty native Australian plants to suggest the most suitable plants to be used in biofiltration system in Australia. Although in general all plants helped in reducing the concentration of nutrients in effluent, each individual plant showed different performance. *Carex appressa* was found as the best performing plant in this study when compared with other plant species. *Carex appressa* is a type of sedge that has both coarse and fine root type with length of up to 60 cm. In addition, this plant has very high tolerance to inundation and drought; therefore, it can survive in almost any condition. There are several studies that supported the finding and usage of *Carex appressa* (Hatt et al., 2009a; Blecken et al., 2010; Payne et al., 2015).

Although the characteristics of vegetation needed for biofiltration system have been studied, the plant selection has not reached its maximum potential due to the required frequent maintenance, such as watering during drought and trimming due to fast growth characteristic. Additionally, since biofilter vegetation should be chosen based on its nativity, many plants have not been explored and thoroughly studied.

2.2.4 Heavy Metals Removal by Biofiltration System

Heavy metals are commonly found in stormwater runoff. Human activities such as mining, processing, of use of metal substances could contribute to the heavy metals pollution in surface water. Additionally, road activities also cause heavy metals pollution such as fluid leaks and vehicle's wheels. Few of the most common heavy metals pollution including zinc (Zn), lead (Pb), chromium (Cr), manganese (Mn), copper (Cu), arsenic (As), nickel (Ni), and cadmium (Cd).

To date, several studies on successful removal of heavy metals by biofiltration systems have been reported in literature (Davis et al., 2003; Pitcher et al., 2004; Dietz, 2007; Hatt et al., 2008; Blecken et al., 2009b; Reddy et al., 2014b). These studies have shown that relatively high percentage of concentration reduction can be achieved by soil media alone. Davis et al. (2003) conducted a study on heavy metals removal by a biofiltration system which consists of sandy loam filter media topped with mulch and the North America native plant *Juniperus horizontalis*. Sandy loam is a loam that is consisted of 5-10% clay, <50% of silt, and 40-50% of sand. The authors reported that the biofiltration system can remove Cu(II), Pb(II), and Zn(II) with more than 99% removal rate. Hatt et al. (2008) compared 6 different filter medias and found that the removal of Cu(II), Mn(II), Pb(II), and Zn(II) in biofiltration columns study could reach values higher than 95%. Moreover, it was concluded that the Mn(II) removal is highly affected by the filter media composition as leaching of Mn(II) was observed when the initial fine sand media was enriched with either hydrocell, perlite, vermiculite, mulch, compost, and charcoal. However, the removal rate of the other 3 heavy metals were not affected. Li and Davis (2008) found that heavy metal removal mainly happens at the upper layer of the filter media. Therefore, replacement of the topsoil with clean soil to reduce the heavy metals accumulation in the biofiltration system was suggested as part of the required yearly maintenance. This finding was supported by another heavy metals removal study conducted by Wang et al. (2017b) in different filter media including sand, zeolite, and sandy loam. The plant used in the study was *Iris ensata* which is a drought-resistant vegetation in the category of herbs. The authors found that the removal of Cu(II), Zn(II), Cd(II), and Pb(II) were all able to reach > 97% at pH 6.05. The accumulation of heavy metals was present mostly at the topsoil which is a mixture of humus and sandy loam (1:1) for all different filter media composition.

Usage of some fine grain materials such as fly ash has been found to improve the performance of heavy metals removal (Zhang, 2006; Yeheyis et al., 2008; Gupta et al., 2009; Haynes, 2014; Li et al., 2014; Grace et al., 2016). Babel and Kurniawan (2003) studied the adsorption capacity of fly ash for Cu(II) and Cr(VI) ions. Authors reported the adsorption capacity of 1.39 mg Cu(II)/g at pH 8.0 and 2.92 mg of Cr(VI)/g at pH 2.0. Hegazi (2013) studied the effect of fly ash dose on removal percentage of metals. Author showed that by increasing the fly ash concentration from 20 to 60 g/L, the percentage removal increased from 46% to 87%, 22% to 76%, 37% to 99%, and 95% to 96% for Fe(III), Pb(II), Cu(II), and Ni(II) ions, respectively.

Besides fly ash, zeolite has been used as one of the most popular fine-grained materials for biofiltration system (Cortés-Martínez et al., 2009; Wu and Zhou, 2009; Koshy and Singh, 2016). Reddy et al. (2014b) investigated the potential of several filter materials in absorbing heavy metal ions from urban stormwater, one of which was zeolite. The results of the experiment showed that zeolite can absorb between 90-100% of heavy metal ions. Most of the heavy metal ions were removed through absorption by the negatively charged surface of the filter material. Haynes (2014) also studied the use of zeolites in removing pollutants from stormwater, especially heavy metal ions. It was found that both natural and synthetic zeolites were effective at absorbing heavy metal ions from an aqueous solution. Since synthetic zeolite requires considerable time and energy, authors suggested that the product's cost for practical application could be a concern.

Reddy et al. (2014a) studied the performance of biochar as an absorbent in stormwater treatment by biofiltration systems. Biochar is a category of charcoal that is produced from vegetation. Authors mentioned that the biochar used in their study was produced by gasification process from waste wood pellets. It was found that biochar performance in heavy metals ions removal is not satisfactory due to its chemical properties and behavior. In this study, the removal percentages of 18, 19, 65, 75, 17, and 24% were achieved for Cd(II), Cr(VI), Cu(II), Pb(II), Ni(II), and Zn(II), respectively. Lim et al. (2015) compared few materials including coconut coir, compost, commercial mix, sludge, and potting soil (loamy sand) for heavy metals ions (Cu(II), Zn(II), Cd(II), Pb(II)) removal. Table 5 compares the properties of filter materials used in the study and its expected lifetime. Since the materials lifespan was heavily affected by the vegetation used and its location, therefore no accurate data was provided. In general, coconut coir would have shorter lifespan in tropical areas due to the quick disintegration. Compost on the other hand, would be consumed by the plants and thus depending on the vegetation type implemented in the system. Two different stormwater concentration dosing were used to observe the behavior of the materials in higher pollutants loading. It was found that the removal percentages in higher pollutants concentration are generally better than the one for low concentrations. Overall, all materials could remove more than 90% of the heavy metals ions in high-concentration loading except for coconut coir which only removed 74% of Cu(II) and 82% of Pb(II). Authors concluded that potting soil and commercial mix are the best choice for biofiltration media in both low or high pollutants loading. However, sludge and compost were only recommended for high-concentration loading.

From the studies reviewed, most heavy metal ions could be removed by biofiltration system media enhanced with many different materials such as fly ash, zeolite, and commercial mix. However, few materials such as biochar and coconut coir were not found to be efficient in removing metal ions due to their chemical properties.

Table 5: Properties of filter materials and its expected lifetime (Lim et al., 2015).

	Loamy sand	**Coconut coir**	**Compost**	**Commercial mix**	**Sludge**
pH	6.44	4.76	6.79	7.17	6.46
Sand (%)	75.3	-	29.3	15.1	90.5
Silt (%)	18.3	-	57.7	5.9	9.2
Clay (%)	2.9	-	0.36	0.12	0.3
Lifespan (year)	>1	0.5-1	0.5-1	Longer than vegetation	-

2.2.5 Nutrients Removal by Biofiltration System

Table 1 shows the typical nutrients (TN & TP) concentration in urban stormwater. In comparison with Malaysian water standard (see Table 3), TN concentration belongs to class IIB while TP concentration mostly fall under class IV. Therefore, nutrients removal performance needs to be considered for biofiltration design. However, unlike heavy metals, early studies revealed that nutrients are difficult to be removed efficiently by soil media alone. Zhang et al. (2008b) studied the performance of fly ash in removing TP for biofiltration laboratory experiment. Authors found that the removal of TP increased significantly from 2% to 85% with the addition of 5% fly ash. The high removal was attributed to the calcium phosphate precipitation at the high pH. Since fly ash has alkaline characteristic, the effluent pH increased from 6.5 to 10.3, thus promoting the precipitation of calcium phosphate. However, very slow infiltration rate was observed (<100 mm/hr) throughout the experimental study. This finding was supported by Kandel et al. (2017) in a field study of three biofiltration cells in United States over 40 storm events. With the addition of 5% fly ash to the filter media, TP removal was improved to 64-75%. However, the infiltration performance was not addressed by authors.

Although TP removal could be done by implementation of certain fine-grained materials, TN removal showed different findings. Inconsistency in nutrients (especially TN) removal efficiency has been reported by several researchers in literature (Hsieh and Davis, 2005; Hatt et al., 2008). Henderson et al. (2007) found that the vegetated soil columns are more effective in nitrogen and phosphorus removal compared to the non-vegetated ones which generally suffer from nitrogen leaching. Nitrogen leaching has been also reported in some other lab studies including Hatt et al. (2007) and Fletcher et al. (2007a). A study by Hsieh et al. (2007b) showed that the presence of mulch in the biofiltration systems would contribute to the leaching of nitrate. Two layers of filter media with higher permeability at the top was suggested by the authors. It was concluded that the proposed design could contribute in generating an aerobic zone in which denitrification might occur due to the microbial activities which in turn would improve the nitrate reduction. In addition, Zhang et al. (2011) reported that the presence of submerged zone could improve the denitrification process thus increasing the removal efficiency of nitrogen-based pollutants.

In another study, Davis et al. (2006) reported that adding 2.5 cm layer of mulch on top of the sandy loam media with *Juniperus horizontalis* resulted in 66% removal of TN. In contrast, Bratieres et al. (2008) showed that TN leaches up to 101% when mulch and compost are added into the system with *Carex appressa* as its plant. Hence, it can be concluded that beside soil media, plants play a major role in TN removal from the system. Read et al. (2008) studied the influence of using different types of vegetations in biofiltration systems nutrient removal performance. Vegetation was found to be effective for phosphorus and nitrogen removal. Table 6 shows the effect of vegetation on nitrate/nitrite (NO_x), Total Dissolved Phosphorus (TDP), and Filterable Reactive Phosphorus (FRP) removal in a biofiltration system studied by Read et al. (2008). As different types of plants could behave differently towards nitrogen absorption, proper plant selection was found to play a significant role in achieving the desirable performance in nutrients removal.

Table 6: Comparison of pollutants concentration of effluent from vegetated and non-vegetated filtration systems (Read et al., 2008).

Pollutant	**Concentration in stormwater (ppm)**	**Concentration in filtered stormwater (ppm)**	
		Non-vegetated Filter	**Vegetated Filter**
NO_x	0.393	0.370	0.083
TDP	0.033	0.080	0.027
FRP	0.026	0.016	0.005

Few studies of nutrients removal under tropical environment have been conducted in the recent years. Ong et al. (2012); Wang et al. (2017a) studied the first established biofiltration system in Singapore during different period of time. With the combination of sandy loam, fine sand, wood chip, and hard rocks media, twelve different vegetation species have been planted as described in section 2.2.3. Throughout August 2009 – July 2010, it was observed that the pollutant concentration can be removed at 46% for TN and 21% for TP. However, during period June 2013 – October 2013, the removal of TN and TP have changed significantly to 25% and 46%, respectively. Authors pointed the difference in the inlet concentration within two different period (1.21 ppm TN and 0.14 ppm TP in 2009, 2.45 ppm TN and 0.20 ppm TP in 2013) and concluded that TN removal is highly affected by the event. Target removal of nutrients can be achieved during small events but not for large events. Salih et al. (2017) studied the potential used of lettuce, spinach, and ivy as pollutant removal in biofilters over duration of 8 weeks. Authors found that lettuce has the highest potential to be used in biofiltration system with the highest nutrients removal capability (57% of NO_3 and 37% of TP). However, the long-term effectiveness of these plants was not addressed. Another study was conducted by GOH et al. (2017) by enhancing standard sandy loam biofiltration media with shredded newspaper and coconut husk. *Hibiscus rosa-sinensis* was used as the vegetation due to fast growth-rate. Throughout 50 weeks of study, authors concluded that the enhanced media improved the water quality to achieve its target removal (50% for TN, 85% for TP) with insignificant changes of hydraulic conductivity.

2.2.6 Stormwater Quantity Control in Biofiltration Systems

Biofiltration systems work by infiltrating water into the soil. Therefore, in a rainfall event, the portion of stormwater that can be captured by such system depends on the infiltration rate. Li et al. (2009) showed that biofiltration systems are capable of mitigating peak flow and reducing the outflow volume from 20-50%. However, authors concluded that the excellent performance can only be achieved for small rainfall events. Authors suggested that for larger rainfall events, higher media volume to drainage area ratio should be used. Bressy et al. (2014) found similar finding where peak flow attenuation in small rainfall events was mainly depending on hydraulic interception.

The hydrological efficiency of biofiltration systems is highly dependent on the infiltration rate of the soil media. Infiltration rate is the water flow rate in soil media for a unit hydraulic gradient and unit cross-sectional area. As it has been discussed in section 2.2.2, the recommended value of infiltration rate is 100-300 mm/hr (FAWB, 2009) and <200 mm/hr (MSMA, 2012). Achleitner et al. (2007) observed the change of infiltration rate of biofiltration system value over time. Authors reported that the final infiltration rate value was half of the initial reading. Biofilters are prone to clogging which normally happens in the interface layer between filter media and underlying soil (Siriwardene et al., 2007; Le Coustumer et al., 2012). The main reason of clogging is migration of sediment particles with size <6 µm into the pores available between bigger particles. Over 72 weeks of experiments, Le Coustumer et al. (2012) observed a significant reduction of infiltration rate with different application of plants as shown in Table 7. It was found that clogging can reduce the effective life time of a biofilter; however, vegetation in biofilters can help in overcoming this problem. However, authors did not specify the reason of the increasing infiltration rate value from biofilters with *Melaleuca sp*. Emerson and Traver (2008) monitored the infiltration rate in a biofiltration system for a period of four years. Authors concluded that biofiltration systems can maintain a reasonably good infiltration rate for at least several years by the help of vegetation. This finding is also consistent with what is reported in FAWB (2009). To confirm these finding, detailed study by Le Coustumer et al. (2009) on several sites in Australia (Melbourne, Brisbane, Sydney) showed that 43% of the measured infiltration rate values are lower than 50 mm/hr, 27% fall between 50 to 200 mm/hr, and 30% are higher than 200 mm/hr. It was concluded that the value of infiltration rate of an operating system is mainly dependent on the initial infiltration rate.

Table 7: infiltration rate of biofilters over 72 weeks of operation (Le Coustumer et al., 2012)

Biofilter type	**$K_{initial}$ (mm/hr)**	**K_{final} (mm/hr)**
No vegetation	199	53
Carex sp.	251	51
Dianella sp.	232	88
Microleana sp.	150	49
Leucophyta sp.	231	66
Melaleuca sp.	155	295

2.3 Conclusion

In general, the presented literature review suggests that there is no universal recipe for designing the biofiltration systems as characteristics of soil, plants, rainfall events, and even stormwater quality can be very different for one environment to another. Despite several successful applications of biofiltration systems all around the world, they are still not so prominent in tropical regions such as Malaysia. In addition, with the typical pollutants concentration in Malaysia urban stormwater runoff (see Table 1), it is understood that few pollutants including heavy metals and nutrients need to be treated before entering the drainage system. To date, no specific profound study has been carried out on the hydrological and pollutant removal performance of biofiltration systems under tropical conditions and there are still lots of issues on designing and maintaining of such systems that need to be addressed. This emerges the need for a profound study to first understand the behavior of such systems under tropical condition and then suggest design criteria (e.g. for selection of proper filter media and plants, maintenance requirement, etc.) for a sustainable and efficient operation under such environment. Therefore, this study has been packaged in three main phases. Non-vegetated columns study in chapter 5 focuses on studying the effect of different soil composition on heavy metals removal and infiltration rate of the system. Since filter media plays a huge role in pollutant removal efficiency, the performance of fine materials in biofiltration columns study is evaluated and compared with conventional biofiltration columns with fine-grained materials. Based on the literature, the usage of fly ash, zeolite, and Hals in biofiltration system could be promising due to its properties as sorbent. Moreover, the application of Hals in biofiltration system will be the novelty of this study. Vegetated columns study in chapter 6 focuses on plants monitoring, selection, and evaluation of their performance in biofiltration system. Finally, chapter 7 focuses on the functionality of biofiltration system by looking into few design parameters for maintenance such as submerged zone and clogging potential.

CHAPTER 3

RESEARCH AIM AND OBJECTIVES

Based on the literature review conducted in Chapter 2, the research gaps in the targeted topic were identified and used to define the aims and objectives of the present study.

3.1 Research Questions

The research questions of this study are three-fold:

1. Considering soil characteristics such as its grain size and distribution, infiltration rate, etc., what type of locally available soil media would work well for developing biofiltration system in tropical area and achieve the required properties including infiltration rate and pollutant removal capability?
2. Considering factors such as growth rate, root length, tolerance against different environment (such as shade, draught, being inundated, etc.), and maintenance requirement, which local plant species are appropriate to be used for biofiltration systems in tropical regions and fulfil the basic requirements such as survivability, low maintenance, and effective contribution to pollutant removal and infiltration rate value?
3. Are the tropical biofiltration systems able to perform efficiently in long-term? What are the potential issues that they may face once operating in tropical regions? Are there any solutions to achieve a sustainable biofiltration system?

3.2 Research Hypotheses

The hypotheses of this study are described as follows:

1. Clay-size materials have been found to have an effective role in pollutant removal specifically for heavy metals. However, they will reduce the infiltration rate. As tropical areas experience intense rainfall events, higher infiltration rate is

needed for biofiltration systems to work efficiently. Therefore, the usage of clay and other very fine materials needs to be minimized.

2. Presence of vegetation has been found as a necessity for nutrient removal from stormwater. Moreover, the root of vegetation has a key role in maintaining the infiltration rate. With higher rainfall intensity in tropical regions, specific root patterns of some local plants are hypothesized to contribute to providing a higher infiltration rate which is a significant need in enhancing the retention as well as pollutant removal.
3. Considering higher rainfall intensity in tropical regions, vegetation is prone to be inundated frequently, especially in wet seasons where plants should tolerate it. This will be one of the key parameters in choosing the proper plant species in tropical regions.
4. High humidity, high average annual rainfall, and not much varying temperature in different seasons in tropical regions are the main reasons for hypothesizing that minimal maintenance would be needed. However, same parameters can also provide convenient conditions for weed invasion.
5. The average life-time of biofiltration systems in found to be around 10-15 years in countries such as Australia and U.S. In tropical area, however, it is hypothesized to be shorter due to the high frequency of usage under tropical regime. It is also hypothesized that there would be novel soil media as well as tropical plant species which can contribute to making the biofiltration systems sustainable for a longer run.

3.3 Objectives

The research objectives of this study are three-fold:

1. To develop an appropriate soil media composition for being used in a tropical biofiltration system through careful assessment of different soil compositions while considering two selection criteria: pollutants removal efficiency and acceptable infiltration rate.

2. To identify appropriate tropical plants for being used in a tropical biofiltration system through assessment of different local species considering factors such as growth rate, root length, pollutants uptake, etc.
3. To find the general needs for survivability of the selected plants which are operating in tropical biofiltration systems through monitoring and assessment of functioning plants under various conditions including seasonal change, direct sunlight exposure, and getting inundated.

3.4 Original Contribution

The original contributions in this thesis are:

1. The first non-vegetated biofiltration study with the use of Hals as fine-grained materials for filter media layer.
2. The first study of Malaysian native plants for biofiltration system.
3. The first seasonal (wet and dry) experimental study on tropical biofiltration systems.
4. The first study on the impact of submerged zone on tropical biofiltration systems.

CHAPTER 4
METHODOLOGY

4.1 Study Organization

The details of the experimental procedures, equipment, and the chemicals, which were used in this research, are described in this chapter. The tropical biofiltration study is categorized into three phases: non-vegetated columns study (Chapter 5), vegetated columns study (Chapter 6), and survivability and functionality study of the system (Chapter 7). Throughout this study, two main parameters were evaluated including infiltration rate and pollutants removal efficiency. Non-vegetated columns study (Chapter 5) focuses on the variety of sand-based filter media compositions with certain percentages of fine-grained materials including fly ash, zeolite, and Hals. The fine-grained materials were introduced to enhance the pollutant removal efficiency as they have high surface area with significant adsorption capacity. Although this study was considered as stand-alone research with non-vegetated soil columns, the ultimate plan was to utilize the findings of this stage in studying the vegetated soil columns (Chapter 6). The focus of the study in Chapter 6 is to evaluate the performance of several tropical native plants used in tropical biofiltration system. It is worth mentioning that Malaysia's weather condition was used in this study. Finally, Chapter 7, focuses on the survivability and the required maintenance criteria for tropical biofiltration system.

4.2 Columns Study Experimental Set up

One of the commonly used materials for soil column studies are PVC pipes due to their low cost and resistant against chemical corrosion (Bratieres et al., 2008; Hatt et al., 2009b). In the non-vegetated columns study (chapter 5), PVC pipes of 160 mm diameter were provided. In comparison with literature, it is common to have PVC pipes with diameter <100 mm for non-vegetated columns to allow 1-dimensional flow to the bottom of the columns (Hatt et al., 2007). However, since small diameter columns would promote preferential flow on the inner wall of the pipes, therefore bigger columns diameter at 160 mm was used. The free board was designed to be 200 mm with 800 mm thickness of layered soil (400 mm of filter media, 100 mm of transition layer, and 300 mm of drainage layer). media following the recommendation of 1000 mm column length by Hatt et al. (2007). To further reduce the potential of preferential flow, the inner walls of all columns were first scratched by sand paper. A single hole was then drilled at the bottom side of each column to act as the outlet which was then equipped with proper piping and valve. After the installation of the outlets, all joints were sealed with water proof glue and sealant to prevent any leakage. The design of non-vegetated column study can be seen in Figure 3(a).

For the vegetated column study (Chapter 6), 200 mm diameter PVC pipes with a height of 1000 mm were provided. The wider columns were chosen to allow more spaces for the plants to live and grow. Freeboard of 165 mm was considered in a way that it doesn’t block the sunlight for plants. The layered-media structure and the inner wall preparation of the vegetated columns followed the non-vegetated ones for the consistency purpose. However, additional feature of submerged zone with 250 mm height from the outlet was introduced in vegetated columns to act as the water storage for plants survivability. Moreover, a perforated pipe was installed inside the columns right behind the outlet to allow the infiltrated water flow out from the system. Figure 3(b) shows the schematic layout of vegetated columns setup used in this study.

4.3 Filter Media Preparation

In the non-vegetated columns study, three batches of mix aggregates (gravel, coarse sand, fine sand) from Klang river were provided by local supplier Era Bina Pelangi. The mix aggregates were used to fill each media layer including drainage layer, transition layer, and filter media as shown in Figure 3(a). The 300 mm thick drainage layer is located at the bottom of the column and mainly consists of gravel to allow water to flow out of the system; the 100 mm thick transition layer contains coarse sand to act as a bridge between drainage layer and filter media layer in order to prevent segregation of small particle in filter media layer to the drainage layer; while the 400 mm thick filter media mainly consists of fine sand for the water filtration process. In order to minimize the clogging potential, each layer in the soil column needed to fulfil the particle size distribution criteria defined based on conventional filtration rules. Payne et al. (2015) proposed two criteria to design the filter, transition, and drainage layer of a biofiltration system. These criteria are defined to avoid particles of a layer with finer grains being washed into a layer with coarser grains (i.e. filter media to transition layer and transition to the drain layer). The two criteria are given in Eqs. (1) and (2):

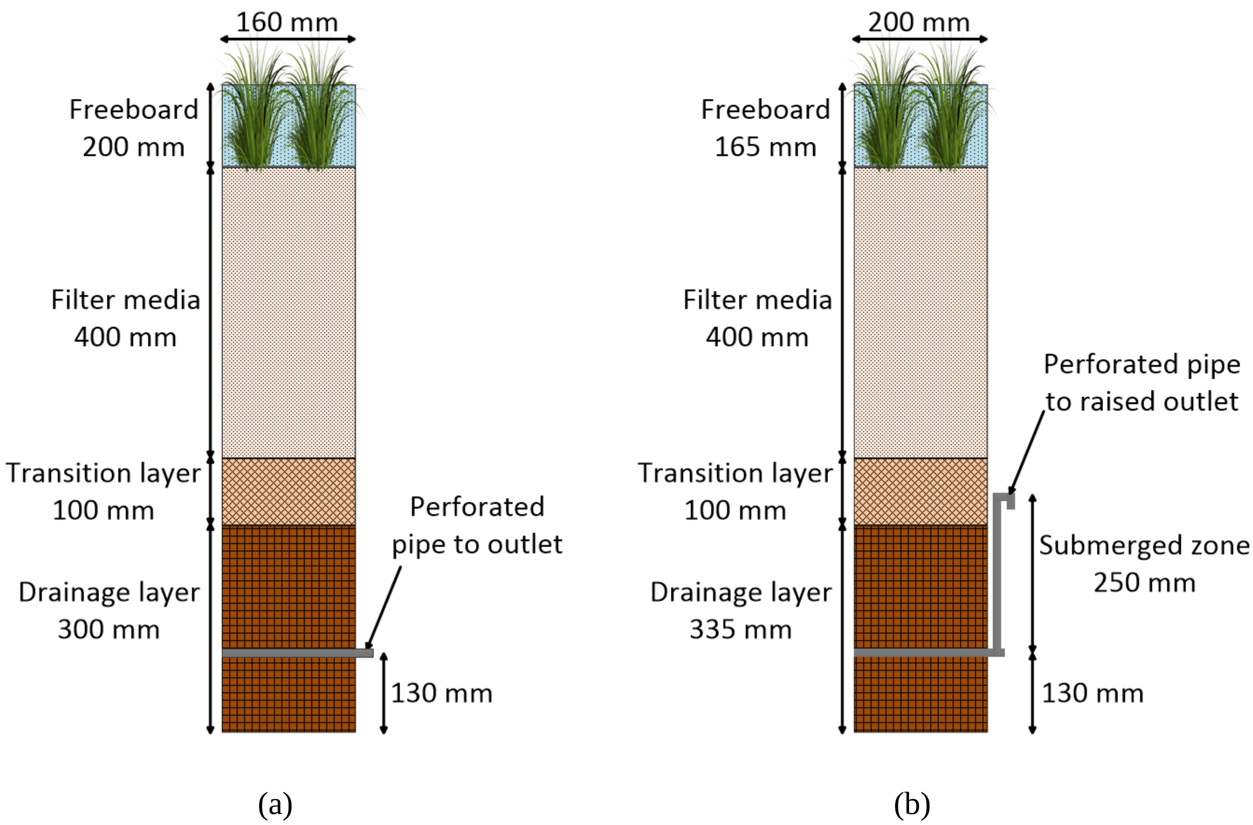


Figure 3: Columns set up: (a) Non-vegetated column study set up;
(b) Vegetated column study set up.

D_{15}(Transition) ≤ D_{85}(Filter) (1)

D_{15}(Drainage) ≤ D_{85}(Transition) (2)

where D_{15} and D_{85} are the 15th and 85th percentile particle size, respectively.

In the non-vegetated columns study, four different fine materials were mixed with filter media including fly ash (FA), zeolite (Z), Hals – Matauri Bay (MB), and Hals – Ultra

Hallo Pure (UHP). Fly ash with surface area of 0.6 m^2/g has been provided from a local supplier EEFFY Marketing (M) Sdn Bhd while natural zeolite is provided by local supplier Kaolin Malaysia Sdn. Bhd. from a natural source in Indonesia with surface area of 17 m^2/g. Two types of Hals are used in this study: Matauri Bay provided by Imery NZ and UltraHallopure provided by I-Minerals Inc. with the surface areas of 22 m^2/g and 47 m^2/g, respectively. According to the literature, fly ash and zeolite have shown promising results in biofiltration system application (see section 2.2.2). Similarly, Hals as member of kaolin group of clay minerals have attracted the attention of few industries such as water filtration and decontamination of industrial effluent (Zhao et al., 2013; Makaremi et al., 2015; Pasbakhsh and Churchman, 2015). However, the usage of Hals as adsorbent in biofiltration system has yet to be studied, thus promoting a novel component in the soil media structure for tropical biofiltration system. These fine-grained materials were added to the filter media based on the weight percentage. For comparison purposes, two different proportions of 2% and 5% of each fine-grained material were adopted. Highest fine-grained materials proportion of 5% were chosen based on literature to reduce the potential of clogging (FAWB, 2009). The experimental columns are denoted as FA2% and FA5% for columns with fly ash, Z2% and Z5% for columns with zeolite, MB2% and MB5% for columns with Hals – matauri bay, and UHP2% and UHP5% for columns with Hals – UltraHalloPure. Additionally, a set of control columns (denoted as C) with no fine-grained materials were also considered. Therefore, total of 9 different soil compositions are considered in this stage of the study. To ensure the reliability of the experimental results, three replicates were made for each of the filter media composition.

To further understand the pollutant removal process as well as the properties of the fine-grained materials on the non-vegetated columns study in chapter 5, characterization study of each fine-grained material (i.e. FA, Z, MB, UHP) was also conducted. The methodology for the characterization study is discussed in section 4.4.

In vegetated columns study (Chapter 6), the media structure was installed similarly with what was used in control columns in non-vegetated columns study. However, four replicates of each planted columns were used instead of three to ensure consistent results due to the implementation of vegetation. In other words, fine-grained materials were removed from the system to keep the soil composition similar in all columns with different plants. Additionally, very fine sand (< 0.15 mm) was removed from the system by sieving to further reduce the clogging potential. Based on Eqs. (1) and (2), the three layers soil media structure for vegetated columns study were designed as shown in Table 8. Table 9 shows the value of D_{15} and D_{85} for the layered soil media. It can be seen that D_{15}(drainage) ≤ D_{85}(transition) as 2.36-3.35 ≤ 2.36-3.35 mm following the required design in Eq.(1). Similarly, D_{15}(transition) ≤ D_{85}(filter) as 0.60-1.18 ≤ 0.60-1.18 mm following Eq.(2).

Table 8: Particle size distribution for each layer of vegetated soil columns in Chapter 6.

Particle Size Range (mm)	**Percentage Distribution by Weight (%)**		
	Drainage	**Transition**	**Filter**
> 4.75	30	-	-
3.35 – 4.75	55	-	-
2.36 – 3.35	10	25	-
1.18 – 2.36	5	60	10
0.60 – 1.18	-	10	20
0.30 – 0.60	-	5	55
0.15 – 0.30	-	-	15

Table 9: The value of D_{15} and D_{85} for layered soil media of vegetated soil columns (mm)

	Drainage	**Transition**	**Filter**
D_{15}	2.36-3.35	0.60-1.18	-
D_{85}	-	2.36-3.35	0.60-1.18

4.4 Characterization of Fine Materials

To find the characteristics of the fine-grained materials used in non-vegetated column study (i.e. FA, Z, MB, and UHP), various characterization tests were made to determine the shape, size, compounds, and morphology of each find-grained material.

4.4.1 X-Ray Diffraction

X-Ray Diffraction (XRD) analysis was conducted to look at the crystalline compounds of each material. This analysis is based on observing the scattered intensity of an X-ray beam hitting the samples as a function of scattered angle, polarization, and wavelength. The waves patterns of the crystalline compounds are obtained from X-ray diffractometer (Bruker, D8 Discover). Following the standard method (ASTM D3906-03, 2013), Bragg's equation $\lambda = 2d \sin \theta$ was used to calculate the samples layer spacing, where λ is the wavelength, d is the distance between each wave in crystalline solid, and θ is the scattering angle. The angle for scanning was ranged from 5 ^{o} to 70 ^{o}. The CuKa radiation source was operated at 40 kV and 40 mA, and the wavelength of the X-ray beam was 0.15418 nm.

4.4.2 Field Emission Scanning Electron Microscopy

Field Emission Scanning Electron Microscopy (FE-SEM) analysis is effectively used in microanalysis of solid materials. This analytical technique is used to investigate the molecular surface structures and electronic properties of solid samples. About 10 mg of samples were dispersed in 10 ml ethanol before placed on a copper grid coated with carbon following SOKI Wiki (2014). Hitachi SU 8010 FE-SEM was then utilized to scan the image of each material with resolution up to 1 nm.

4.4.3 X-Ray Fluorescence

X-Ray Fluorescence (XRF) is a process where the electrons in the sample are displaced from their atomic orbital positions, resulting in the release of energy burst that express the characteristic of a specific element. XRF can typically analyze elements from sodium to uranium with concentration detection limit from part per million up to high percent. XRF test was done in this study to look at the elements present in the samples of each fine-grained material following the standard method (ASTM E1621, 2013). Shimadzu Fluorescence Spectrophotometer μ-EDX 1400 was used to analyze each fine material in this study.

4.4.4 Grain Size Analysis

Grain size analysis is common in geotechnical engineering to find the distribution of different particle size in a soil sample. In ASTM standard, grain size analysis for particles with diameter > 0.075 mm can be done by standard sieve analysis ASTM C136M (ASTM standard, 1998b) while for particle < 0.075 mm standard Hydrometer Test, ASTM D422-63 (ASTM Standard, 1998a) is recommended. In the sieve analysis, a sample of the soil is sieved through multiple sieves with different opening size. Following the criteria given in Eqs(1) and (2), sieve analysis was conducted to ensure the soil composition satisfies the conditions given. Prior to the sieve analysis, aggregates were dried for 24 hours in a laboratory oven at 105 ^{o}C for 24 hours following the standard method (ASTM standard, 1998b). The sieve analysis was conducted by using the standard sieves and sieve shaker. Table 10 shows the standard sieves number and their corresponding opening sizes that are used in particle size analysis.

Table 10: The standard sieve number and their opening size used for particle size analysis.

Sieving number	**Sieve opening size (mm)**
4	4.750
6	3.350
8	2.360
16	1.180
30	0.600
50	0.300
100	0.150
200	0.075

In hydrometer test, the portion of soil samples that is smaller 0.075 mm in diameter is mixed in a solution of a dispersing agent in demineralized water. After preparation, the mix needs to be transferred to a standard sedimentation cylinder and the hydrometer is carefully inserted into the cylinder. Readings on hydrometer is related to the buoyancy force which is depending on the specific gravity of the mix. By a standard procedure and the prescribed equations, the readings can be used to find the distribution of particles with different diameter size. In this study, both sieve and hydrometer tests were carried out to find the grain size distribution for fly ash, zeolite, MB, and UHP.

4.5 Infiltration Rate Measurement

Infiltration rate is one of the soil properties which describes the average velocity of fluid (water in this study) flow through porous media (soil in this study). Infiltration rate is generally expressed in velocity units such as cm/sec, m/sec, mm/hr, etc. Several parameters such as fluid viscosity, pore size distribution, void ratio, roughness of particles, and the degree of soil saturation may have an effect on infiltration rate (Das, 2010). Table 11 shows the typical infiltration rate for different types of saturated soils.

Table 11: Typical infiltration rate values for different saturated soils (Das, 2010).

Soil Type	Infiltration rate (mm/hr)
Clean Gravel	3600000 – 36000
Coarse Sand	36000 – 360
Fine Sand	360 – 36
Silty Clay	36 – 0.36
Clay	<0.072

There are two laboratory tests to determine the infiltration rate namely: Constant-Head Test which is suitable for coarse grain soil such as gravel and sand; and Falling-Head Test which is commonly used for fine grain soil such as silt and clay. As the filter media of this study falls in the domain of coarse grain soil material, the constant-head test was adopted to measure the infiltration rate of the soil columns. In this method, constant head water should be provided on the soil sample following the standard (ASTM D2434-

68, 2006). The columns were poured with ≈8 L of tap water until saturated (indicated by no bubble on the top of the surface). Once the system is in saturated condition, infiltration rate measurement was done by collecting the outlet water for certain period. Infiltration rate can be calculated by Eq. (3):

$$K = \frac{V}{At} \tag{3}$$

where, *K* is infiltration rate in mm/hr; *V* denotes the volume of collected water in mL; *A* is the cross-sectional area of the soil sample in mm^2; and *t* corresponds to the duration of water collection in seconds. For any measurement, it is noted that three replications should be done for consistency purpose. Additionally, the outlet water was not recycled to maintain the tap water characteristic throughout the measurement. Figure 4 schematically shows the typical setup in a constant-head test. The constant-head test was used throughout the experiment for both non-vegetated and vegetated columns study.

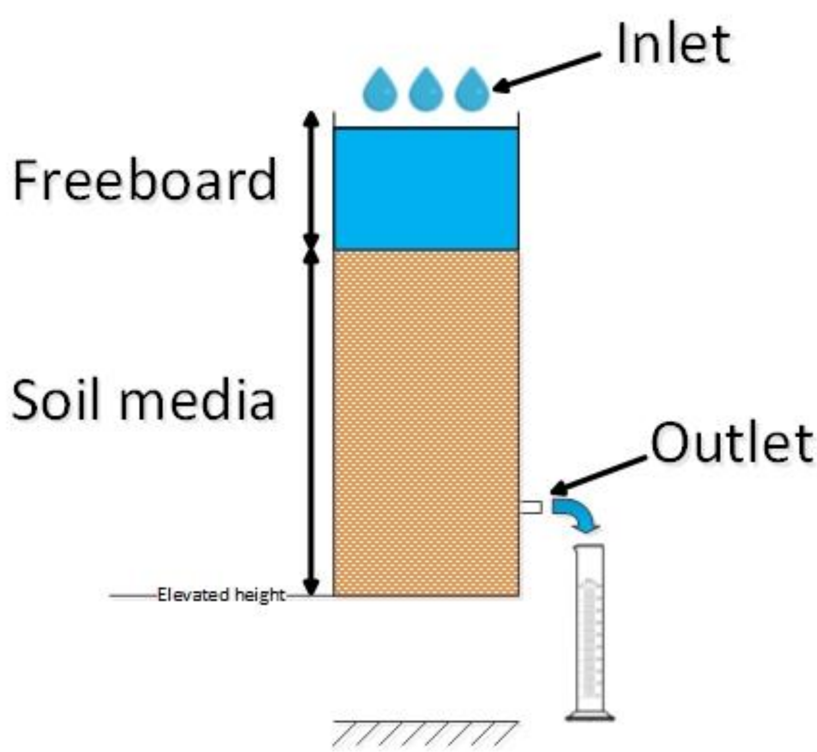


Figure 4: Constant-head test for measuring infiltration rate.

4.6 Stormwater Quality Measurement

Sampling of the stormwater was done based on the volume of infiltrated water. Timely based sampling was avoided due to the fact that different columns have different infiltration rates. Throughout the experimental study, sampling was conducted by collecting the infiltrated water until the outlet stream has no flow. The collected water was then transferred into 100 mL bottles for analytical test. The samples obtained from each column were tested with Perkin Elmer Optima-8000, ICP-OES for finding the pollutant concentration. Seven calibration points were used including 0, 0.01, 0.05, 0.10, 0.20, 0.50, and 1.00 ppm. The maximum of 1 ppm was taken since the concentration of the synthetic stormwater does not show any values above 1 ppm. The ICP-OES machine can detect targeted heavy metals with detection accuracy up to 0.001 ppm. The procedure for ICP-OES test was taken from standard method (UOP714-07, 2007). For nutrients detection (Chapter 6), Hach method 10071 and Hach method 8190 were used to measure both TN and TP, respectively. The machines used to perform these tests were digester DRB200 and Ultra Violet – visible spectroscopy (UV-vis) DR6000. The detection limits for both TN and TP are 0.01 ppm.

4.7 Synthetic Stormwater Concentration

Synthetic stormwater was used for both non-vegetated and vegetated columns study. There are several reasons why synthetic stormwater are preferred to be used in laboratory scale study of biofiltration systems rather than the real stormwater. According to FAWB (2009), one of the main reasons is the fact that maintaining the chemical and physical characteristics of stormwater such as sediment particle size distribution and concentration of pollutants is not an easy task. For example, due to the first flush phenomenon, stormwater generated in the first few minutes of a rainfall event could be highly polluted; however, after a certain period of time, pollutants concentration would decrease significantly. In this study, synthetic stormwater was made by adding specific chemicals to the dechlorinated water. In non-vegetated columns study (chapter 5), only heavy metals (Zn, Pb, Ni, Fe, Mn, Cu) were considered as pollutants since non-vegetated soil columns are not meant to remove nutrients. Therefore, nutrients (TN, TP) were added only for vegetated columns study (Chapter 6). Since both non-vegetated and vegetated soil columns are found to perform well in removing total suspended solids based on literature, it was decided to exclude them from synthetic stormwater used in this study.

Duncan (1999) and Taylor et al. (2005) reported the average pollutants concentrations based on reviewing catchments located all around the world. In Malaysia, however, very limited data on stormwater concentration is available in literature. A study on a Malaysian catchment located in Johor state conducted by Yusop et al. (2005) was used for comparison purposes with the world average data. To come up with certain pollutants concentration of the synthetic stormwater, it was decided to consider the highest recorded concentrations from the afore-mentioned studies (see Table 2). Table 12 summarizes the pollutants concentrations used to prepare synthetic stormwater of this study with the corresponding chemicals to be mixed according to FAWB (2009). It is worth mentioning that due to the presence of chlorine (Cl) in the chemicals, dechlorinator Sodium thiosulfate pentahydrate ($Na_2S_2O_3.5H_2O$) was used to neutralize the chlorine level. In addition, the pH of the synthetic stormwater was kept between 6-7 for consistency purpose.

Table 12: Pollutants concentration, source, and classification for artificial stormwater used in the study.

Pollutants	Target concentration (ppm)	Chemicals (FAWB, 2009)	Class
TN	4.32	NH_4Cl; KNO_3; $C_6H_5NO_2$	Class V
TP	1.12	KH_2PO_4	Class IV
Zn(II)	0.25	$ZnCl_2$	Class IIB
Pb(II)	0.14	$Pb(NO_3)_2$	Class IIB
Ni(II)	0.03	$Ni(NO_3)_2.6H_2O$	Class IIB
Fe(III)	0.86	$Fe(NO_3)_3.9H_2O$	Class IIB
Mn(II)	0.23	$Mn(NO_3)_2.H_2O$	Class V
Cu(II)	0.15	$CuSO_4.5H_2O$	Class IV

In addition, as it can be seen in Table 12, the concentration of TN and Mn(II) in synthetic stormwater fall under class V while for TP and Cu(II) fall under class IV. This figure for Zn(II), Pb(II), Ni(II), and Fe(III) fell at class IIB of Malaysia discharge water standard (see Table 3). Although few pollutants are already fulfilling the class IIB criteria, these pollutants were still included in this study to assess the ability of soil and plants to reduce the concentration of each pollutant.

4.8 Experimental Stormwater Dosage

To determine the stormwater dosage for watering the columns, a method proposed by Urban Stormwater Management Manual for Malaysia (*Manual Saliran Mesra Alam Malaysia*, MSMA) was adopted. A hypothesized small squared-shape fully urban catchment with area of 625 m^2 (25 * 25 m) was considered. It was assumed that it is parking with a paved surface with longitudinal slope of 2% towards one of its side. Recommended by MSMA (2012), 3-months ARI was considered to calculate the design rainfall for this study. Due to the limitations of the design charts in MSMA, it was assumed that the parking is located in city of Ipoh, Perak, Malaysia. The infiltration rate of 100 mm/hr was assumed as the operating value for the designed biofiltration system following the recommendation by MSMA (2012). It is worth mentioning that, the adopted infiltration rate is intentionally underestimated compared to the measured values resulted in initial trials of the experimental set up of this study. This conservative value accounts for the potential clogging that may happen after some time of operation. Considering the above-mentioned assumptions, the required size of a biofiltration basin to capture the 3-months ARI event was calculated. Then, the captured volume of water was translated to the lab scale soil column using the area ratio of A_{column} / A_{basin}. This value will determine the dosage used in each chapter of the study. The detailed dosage calculation for chapter 5 and 6 are shown in Appendix B.

4.9 Plants Selection, Monitoring, and Installation in Columns

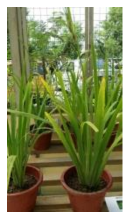
Following FAWB (2009) and MSMA (2012), several criteria were adopted for plant selection including low maintenance, good root penetration, ability to absorb pollutant loads, and the ability to survive in highly variable soil moisture and ponding conditions. Considering the above-mentioned criteria and the availability in Malaysia, total of ten different plants were purchased from local supplier Fern Landscape as candidates and kept in a greenhouse in Monash University Malaysia for further investigation. Eight replicates of each plant were provided for consistency check of the observations. In monitoring stage, plants were kept in pots with nutrient-rich soil. Due to the environment difference between pot and natural soil with higher soil moisture, plants were initially watered twice a day by 300 ml tap water each. After 2 weeks, a daily watering (300 ml) practice was adopted to let the plants adapt to less water. No extra fertilizer was used during the monitoring stage. Table 13 shows the selected candidate plants of this study.

After the monitoring stage, few plants species were selected to be used in the columns study based on the survivability factor. These plants were then transferred from pot to the filter media layer of soil columns. The nutrient-rich soil from the pot was removed as much as possible by washing the root with tap water. After that, for each column, 150 mm deep hole was dug on top of the filter media to accommodate the root of the plant before putting the media back. Care was taken to minimize the root disturbance. Period of 2 weeks was considered for establishment of plants in their new environment which is called as adaptation period in this study. During this period plants were watered on daily basis with synthetic stormwater. The actual sampling and testing on vegetated columns only started after adaptation period. In this study, four replications of the vegetated soil columns were considered along with another 4 control columns without vegetation for comparison purposes. In addition, 2 of the 4 vegetated soil columns were made from transparent acrylic for future observation on the plant root growth. However, the outer wall of the transparent columns were covered with plastic sun shade during experimental study to maintain the same environmental condition between transparent and non-transparent columns.

Table 13: Selected candidate plants of this study.

Plants common name / scientific name	Picture	Characteristic
Bamboo grass / *Bambusoideae*		Plant height: 30 Root structure: thin, massive
Ti plant / *Cordyline fruticose*		Plant height: 40 Root structure: thick, massive
Citronella grass / *Cymbopogon nardus*		Plant height: 65 Root structure: thin, sparse
Umbrella plant / *Cyperus alternifolius*		Plant height: 80 Root structure: thick, sparse
Rosea variegate / *Graptophyllum pictum*		Plant height: 20 Root structure: thin, sparse
Parakeet flower / *Heliconia psittacorum*		Plant height: 70 Root structure: thick, sparse

Table 13 continued…

Pink chinese hibiscus / *Hibiscus rosa-sinensis*		Plant height: 55 Root structure: -
Spiler lily / *Hymenocallis speciose*		Plant height: 40 Root structure: thick, sparse
Iris yellow / *Iris pseudacorus*		Plant height: 50 Root structure: -
Devil's backbone / *Pedilanthus tithymaloides*		Plant height: 65 Root structure: thin, sparse

CHAPTER 5

NON-VEGETATED COLUMNS STUDY

5.1 Introduction

In this chapter, the study is focused on non-vegetated soil columns. The aim was to identify the proper soil composition for being used in a tropical biofiltration system. Therefore, two main parameters were evaluated including infiltration rate and heavy metals removal efficiency. In this chapter, synthetic stormwater dosage was calculated to be 8 liters per event (based on the assumptions and discussions in section 4.8). The detailed calculation is provided in Appendix B. To evaluate the performance of the biofiltration columns, a sand-based filter media structure was considered following the recommendation by FAWB (2009) as shown in Table 4 (see section 2.1). In addition, fly ash (FA), zeolite (Z), and Hals (MB & UHP) were used as fine-grained materials. The fine-grained materials were introduced to enhance the pollutant removal efficiency by their high surface area with significant adsorption capacity. The findings of this stage of study (non-vegetated system) on the pollutant removal mechanism are utilized later for vegetated columns study in Chapter 6.

5.2 Particle Size Distribution of Filter Media

Based on the available materials discussed in section 4.3, the three batches of mix aggregates (gravel, coarse sand, and fine sand) were tested by sieve analysis to check the suitability with the size distribution requirement and the results are summarized in Table 14. As it can be seen, 45% of gravel aggregates are with diameter > 4.75 mm. In the coarse sand, particle size between 0.60 – 1.18 mm has the highest portion of 39%. As for filter media, both particle size ranges of 0.30 – 0.60 mm and 0.60 – 1.18 mm have 32% portions individually. Based on Eqs. (1) and (2), it can be seen that this media is fulfilling the requirement suggested by FAWB (2009) to minimize the potential of clogging as D_{15} (coarse sand) ≤ D_{85} (fine sand) and D_{15} (gravel) ≤ D_{85} (coarse sand). Therefore, the gravel, coarse sand, and fine sand aggregates were considered as suitable for being used for drainage (300 mm), transition (100 mm), and filter media (400 mm) in all soil columns of this study, respectively.

Table 14: Particle size distribution of three available mix aggregates.

Particle Size (mm)	Percentage Distribution by Weight (%)		
	Gravel aggregates	Coarse sand aggregates	Fine sand aggregates
> 4.75	45	-	-
3.35 – 4.75	15	-	-
2.36 – 3.35	20	2	-
1.18 – 2.36	15	17	4
0.60 – 1.18	5	39	32
0.30 – 0.60	-	21	32
0.15 – 0.30	-	21	25
< 0.15	-	-	7

5.3 Characterization of fine materials

To be able to assess the impact of adding fine material on pollutants removal, it is necessary to first know their characteristics. This characterization procedure will also help to better understand the removal process of fine-grained material in the soil columns.

5.3.1 XRD Test results

XRD patterns of Hals, FA and Z are illustrated in Figure 5. The main reflections of Hals appeared at the diffraction angles (2θ) of 11.5 ° (d = 7.58 Å), 20° (d = 4.4 Å) and 24.6° (d = 3.6 Å) which correspond to the crystallographic orientations of 001, 020 and 002, respectively (De Silva et al., 2015; Yuan et al., 2016). The reflection at 2θ = 11.5 ° has a basal spacing of 7.58 Å which is ascribed to the dehydrated form of Hals. Apart from the main reflections of Hals, traces of quartz correspond to the 2θ at 26 ° and 60 ° present in the diffraction patterns, which indicates the level of purity of Hals. The X-ray diffraction pattern of Z (2θ between 10 and 35 degrees) shows the presence of for clinoptilolite and quartz, but the predominant crystalline phase is clinoptilolite. The XRD characteristics of the FA is dominated by the presence of Quartz and a bit of the Mulite phase. Quartz is considered as the main mineral present indicated by the sharp peak near 2θ = 26.5 °.

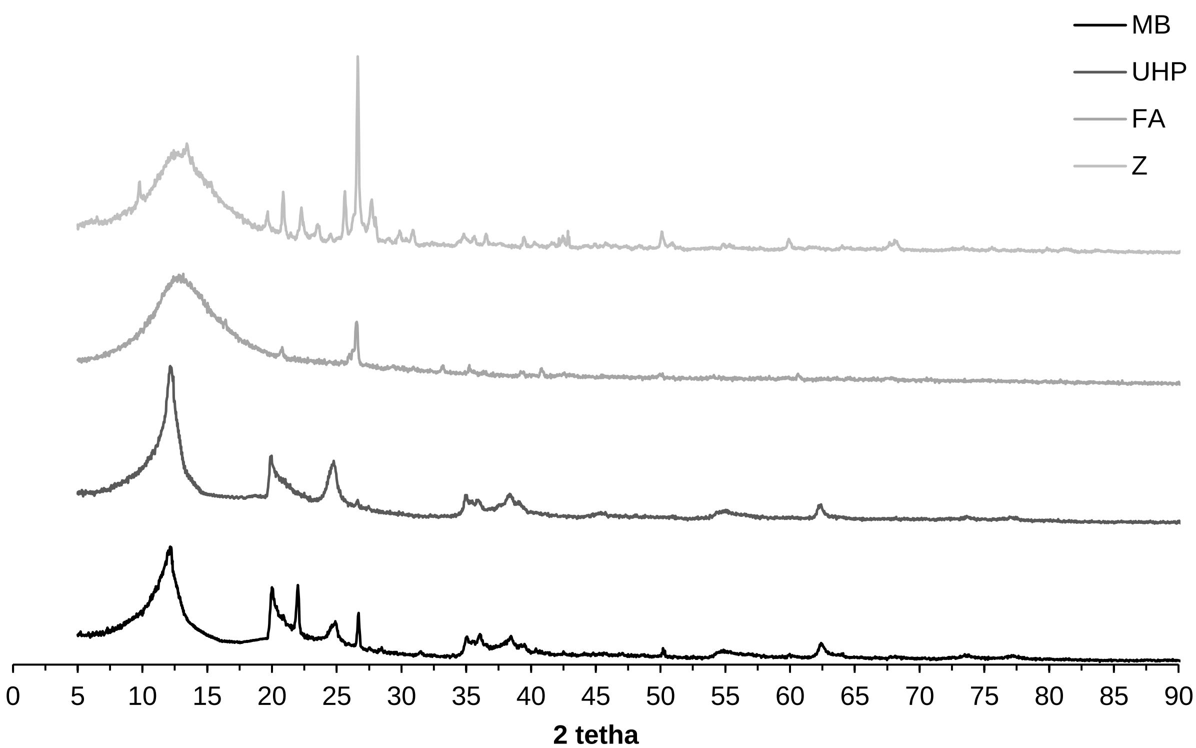


Figure 5: X-ray diffraction (XRD) results for the four minerals used in this study: Fly ash, Zeolite, Halloysite MB, and Halloysite UHP.

5.3.2 Morphological analysis

Figure 6(a-d) shows the morphologies of the fine materials. As it can be seen in Figure 6(a), the FA particles are naturally grouped together and made bulky shape particles with size of 50 μm to few hundreds μm. The surface of this bulky shape particles are full of much smaller size particles (1 to 4 μm). For Z (See Figure 6(b)), the spherical particles with diameter ranging from 10 to 200 μm. The surface of these spherical particles is covered with smaller particles of size 1 to 2 μm. As it can be seen in Figure 6(c) & (d), MB halloysite is ranged from 50 nm – 2 μm long, 20 – 100 nm outer diameter

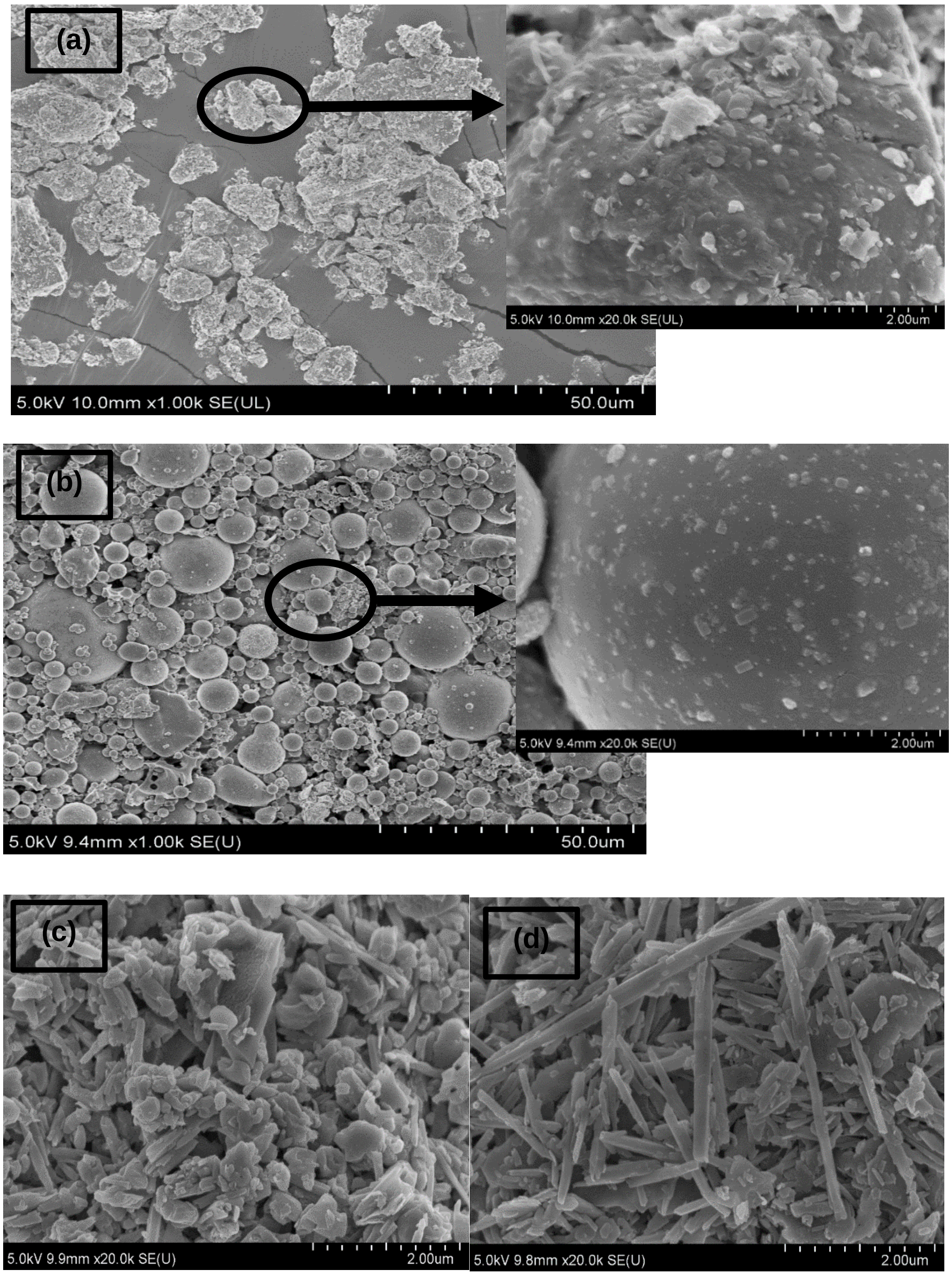


Figure 6: Scanning electron microscopy (SEM) images of four minerals used in this study: (a) Fly ash, (b) Zeolite, (c) Halloysite MB, (d) Halloysite UHP.

and 5–30 nm inner diameter; however, UHP particles are longer (up to 4 Micron sometimes) and thinner. The aspect ratio and surface area of UHP is much higher than MB halloysite and that can be one of the main reasons for the better adsorption record for UHP halloysite. As reported by Pasbakhsh et al. (2013), the volume percentage of lumen structure of Hals may be as high as 15% although the effect of lumen on the filtration data was not observed in this study but this can be a topic of a future study. Figure 6(c) & (d) show the various morphological shapes of halloysite nanotubes. The most common Hal morphology for MB is hollow tube while short tubular, pseudo-spherical, platy and semi-rolled Hals have also been observed in MB micrographs. As for UHP the most dominant morphology was the thin tubes and very less impurity has been observed in the micrographs.

5.3.3 XRF test results

The results of X-ray fluorescence (XRF) test for the four minerals used in this study are presented in Table 15. It is noted that three replications of the test were conducted to ensure the accuracy of the finding. As it can be seen, FA is mainly consisted of SiO_2 (58.59%) and Al_2O_3 (23.41%). The other two important compounds in FA are Fe_2O_3 (5.67%) and CaO (4.74%). Similar to FA, Z also mainly consists of SiO_2 (75.19%) and Al_2O_3 (14.49%). The next two important chemicals in Z are K_2O (3.26%) and CaO (2.22%). The two main compounds for MB and UHP are also SiO_2 and Al_2O_3. For MB, the percentage of SiO_2 is 60.14% while it is 55.55% for UHP. However, the percentage of Al_2O_3 in both MB and UHP is much higher than the ones in FA and Z (38.79% for MB and 41.45% for UHP). XRF analysis showed that the percentage of other minerals in MB and UHP are very small (below 0.5%) except Fe_2O_3 in UHP which is 1.63%.

Table 15: X-ray fluorescence (XRF) test results for the four minerals of this study: Fly ash, Zeolite, Halloysite MB, and Halloysite UHP.

	FA (%)	Z (%)	MB (%)	UHP (%)
Na_2O	0.875	1.396	0.063	0.060
MgO	1.486	0.905	-	0.179
Al_2O_3	23.412	14.760	38.786	41.447
SiO_2	58.587	75.189	60.136	55.554
P_2O_5	1.128	0.024	0.277	0.032
SO_3	0.612	-	0.080	0.102
Cl	-	0.010	0.043	0.037
K_2O	1.587	3.260	0.019	0.400
CaO	4.740	2.224	0.012	0.070
Sc_2O_3	0.013	-	-	-
TiO_2	1.119	0.177	0.114	0.384
Cr_2O_3	0.021	-	-	-
MnO	0.056	0.037	-	0.017
Fe_2O_3	5.670	1.907	0.384	1.630
NiO	0.025	-	-	-
CuO	0.015	-	-	-
ZnO	0.023	0.007	-	0.005
Ga_2O_3	0.007	-	0.042	0.045
Rb_2O	0.015	0.012	-	0.004
SrO	0.270	0.042	-	0.003
Y_2O_3	0.009	0.004	0.004	0.003
ZrO2	0.104	0.013	0.023	0.003
Nb_2O_5	0.005	-	0.007	-
BaO	0.182	0.033	-	0.027
Nd_2O_3	0.026	-	-	-
PbO	0.013	-	-	-
ThO_2	-	-	0.010	-

5.3.4 Grain size analysis

The results of sieve and hydrometer tests for the four fine materials of this study are shown in Figure 7. The horizontal axis shows the particle diameter in mm while the vertical axis shows the percentage passing or the percentage of particles (in weight) that have diameter equal or smaller to a specific size. A curve which is located more towards the right side of the figure has bigger particle size compared to the one located in the left side of the figure. Looking at the sieve analysis results on particles bigger than 0.075 mm, MB has the highest particle size followed by UHP, Z, and FA. Based on sieve analysis, 25.2%, 41.7%, 53.1%, and 9.81% of the particles are smaller than 0.075 mm in MB, UHP, FA, and Z, respectively. This portion is the one that needs hydrometer tests. Looking at that portion of particles, MB is finer than FA and Z. It is worth mentioning that the hydrometer test failed for UHP since the particles were so small that didn’t settle down during the experiment. Hydrometer results confirms that MB and UHP have very fine particles smaller than 0.075 mm that can contribute in heavy metal ions absorption while they have also a good portion of big particles that can contribute in higher infiltration rate. This capability will be advantageous for the two Hal of this study compared to FA and Z. Comparing with literature, 80% of the FA particles size should be <0.005 μm (Aboustait et al., 2016). However, less than 10% of FA in this study belong to the afore-mentioned size. This shows that the FA used in this study is considered as coarse FA. Similarly, a study by Floros et al. (2017) on natural zeolite characteristic showed that 70% of Z size should be <0.063 μm. However, in this study, only 10% of the particle size were following the literature. It is worth mentioning that with the addition of 2% or 5% of fine-grained materials to the filter media, the requirement for particle size distribution as shown in Eqs. (1) and (2) are still satisfied, thus will be applied in this experimental study.

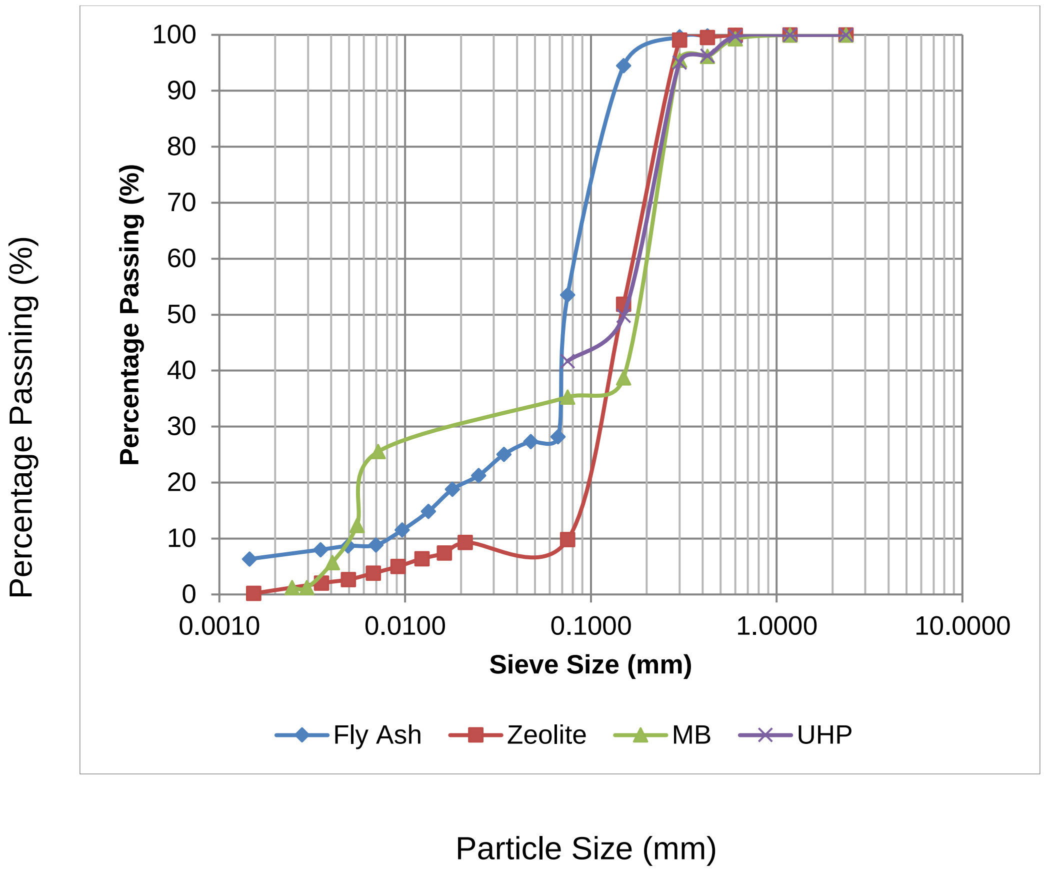


Figure 7: Particle size distribution for FA, Z, MB, and UHP resulted based on sieve and hydrometer tests.

5.4 Infiltration Rate Results

The results of infiltration rate for the columns with 2% and 5% fine-grained materials are presented in Figure 8. As it can be seen, by increasing the percentage of fine material from 2% to 5% the infiltration rate drops in all column types of this study. This is due to the higher presence of fine materials that fills up the pores in the filter media thus slowing down the infiltration process. In general, columns with MB content shows the highest infiltration rate, followed by UHP, Z, and FA. Columns with 2% MB yielded the highest infiltration rate value at 364 mm/hr while columns with 5% FA showed slowest infiltration rate of 98 mm/hr. This finding is matching with the results of grain size analysis (Section 5.3.4) where MB was comparatively the coarsest out of four materials used in this study followed by UHP, Z, and FA. Therefore, it is evident that material with larger particles gives higher infiltration rate and using 2% of fine-grained material produces relatively higher infiltration rate compared to 5%.

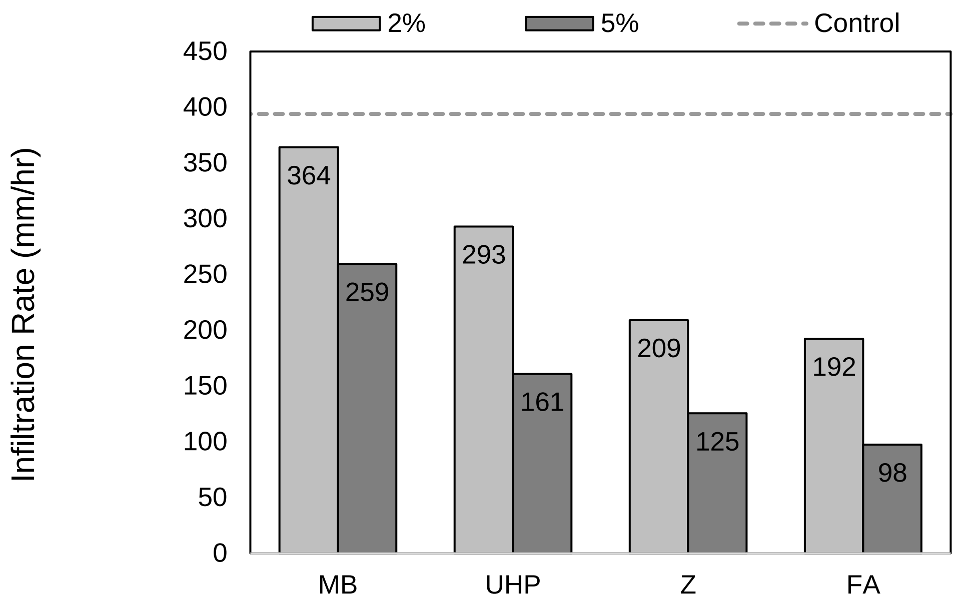


Figure 8: Average infiltration rate values for columns with different types and percentages of fine material.

5.5 Heavy metal ions removal by soil media

Although natural stormwater contains other pollutants such as nutrients, sediments, oil and grease, and pathogens, this study focuses only on the heavy metals pollutants by preparing synthetic stormwater. However, it is believed that the proposed soil media would contribute to the removal process of other pollutants. This is especially true for MB and UHP where the surface of the inner lumen carries a +ve charge which attracts anions. Additionally, oil absorption capacity of Hals is generally high (especially UHP) with value of higher than 90 g oil/100 g UHP. Besides that, the mixture of pollutants may potentially affect the removal process due to competitive adsorption. Rangsivek and Jekel (2008) studied the competitive adsorption between natural organic matter (NOM) and heavy metals such as Cu(II) and Zn(II). Authors concluded that competitive adsorption occurred at slightly acidic pH of 5.5. However, in real application of biofiltration system, competitive adsorption is not a concern due to the few reasons such as neutral pH, low content of oil and grease in natural stormwater (Duncan, 1999), and the present of vegetation which is the primary role of nutrients uptake (Read et al., 2008). There is a potential issue of clogging in the system due to the presence of suspended dust particles from the sand aggregates which eventually may affect the infiltration rate. However, studies have shown that root propagation of plants could minimize the impacts (Siriwardene et al., 2007; Le Coustumer et al., 2012). Therefore, this focused study is unlikely to have significant discrepancy in the result due to the competitive adsorption.

The heavy metal ions removal performance for different soil column type was measured in terms of percentage removal of each individual metal ions. The average value of percentage removal was calculated for the three replicates of each type. This procedure was repeated in the 3 rounds of experiment and the average of these 3 was calculated for comparison. For columns with different types and portions of fine materials, the average percentage removal of Ni(II), Zn(II), Pb(II), and Cu(II) are compared in Figure 9(a-d), respectively.

All column types could remove Pb(II) and Cu(II) as the removal percentages were above 95%. In comparison with literature, Hegazi (2013) found that FA contributes to Pb(II) removal by 76% and Cu(II) removal by 99%. Another study by Reddy et al. (2014b) showed that natural zeolite could help in heavy metal ions removal up to 90-100%. It was concluded that increasing the proportion of fine materials from 2% to 5% doesn’t have any significant impact on removing Pb(II) and Cu(II). It was found that control columns alone can remove Pb(II) and Cu(II) with more than 95% efficiency; thus, the contribution of fine materials in improving the Pb(II) and Cu(II) removal is minimal. For Ni(II) removal, UHP and FA columns performed slightly better than columns with MB and Z. It was found that the increase in fine material proportion from 2% to 5% slightly deteriorates the performance of Ni(II) removal for columns containing MB and Z. For Zn(II) removal, all columns showed removal percentages equal or bigger than 95% except for MB where the performance was at 89% removal rate. It was also concluded that the increase in fine material proportion has not any considerable influence on Zn(II) removal.

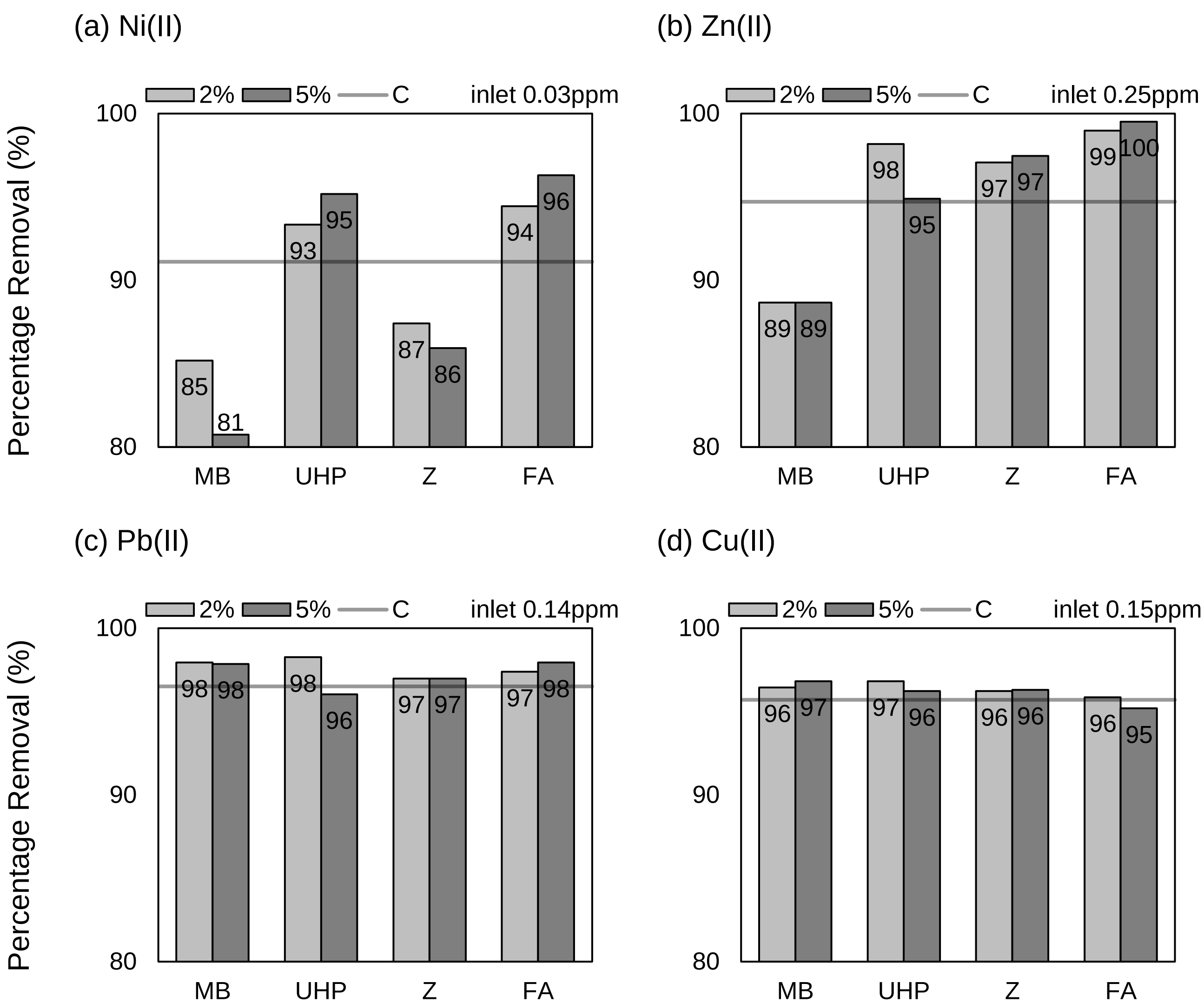


Figure 9: Average percentage removal of (a) Ni, (b) Zn, (c) Pb, and (d) Cu ions in columns with different types and proportions of fine materials.

Figure 10 compares the average percentage removal of Fe(III) in columns with different types and portions of fine materials. As can be seen, all columns except the one with 5% of UHP performed better than control columns in removing Fe(III). The performance comparison between control columns and columns with fine-grained materials was significant (>20% adsorption difference except for 5% UHP). This is due to the fact that Fe presents as Fe(III) while other metals present as M(II). The two main functional groups in the fine-grained materials which is SiO_2 and Al_2O_3 play a huge role in the adsorption process. Mohan and Gandhimathi (2009) studied the adsorption mechanism of metals to both functional groups and found that the surface of SiO_2 has a high affinity towards metal ions. Additionally, Si has a very strong affinity for electrons due to its central ion Si(IV). Weak basic is formed when O_2 are bound to the Si(IV), thus silica surface would act as a weak acid. On the other hand, surface silanol (SiOH) was formed when O_2 react with water. Since -ve charges silica was observed at neutral pH, thus the contents of the fine-grained materials are at the negative charges (silica, alumina, iron). The adsorption mechanism of Fe(III) could be presented in Eqs. (4) to (7).

$$\equiv SiOH + OH^- \rightarrow \equiv SiO^- + H_2O \quad (4)$$

$$\equiv AlOH + OH^- \rightarrow \equiv AlO^- + H_2O \quad (5)$$

$$3(\equiv SiO^-) + Fe^{3+} \rightarrow (\equiv SiO)_3Fe \quad (6)$$

$$3(\equiv AlO^-) + Fe^{3+} \rightarrow (\equiv AlO)_3Fe \quad (7)$$

Among the four different types of columns in this study, the ones with MB and FA were able to remove Fe(III) quite well and increase in proportion from 2% to 5% improved the performance significantly. Although FA has the highest content of Fe_2O_3 (5.67%, see Table 15), no leaching of Fe ions was observed due to the neutral pH condition (≈7). This finding is similar with a study conducted by Seidel and Zimmels (1998) where Fe leaching in FA only occurred when pH<1.5. Izquierdo and Querol (2012) reported similar finding where less than 10 mg Fe/kg FA was leachable when pH≈7. However, column with Z performed worse than MB and FA for both 2% and 5% proportions. Among the four different types of columns, UHP showed quite different trend as an increase in proportion from 2% to 5% had a reverse impact on Fe(III) removal. For columns with 2% UHP, the removal percentage was 99% while it dropped significantly to 37% for columns with 5% UHP. Further investigation showed that Fe_2O_3 presents in UHP in three different forms including (1) the crystal lattice of kaolin and halloysite substituting for Al, (2) in trace of mica, and (3) as free ferric hydroxide (Limonite) (Panychev, 2006). Since limonite is very fine, it appears as colloidal particles which eventually may be washed out from the system. Obviously, this is more readily available in columns with 5% UHP which is practically detected as Fe(III) leaching from the columns. Additionally, pH has a big role in solubility of Fe ions. In 2% UHP, Fe is present as Fe(III) which is likely to be captured whereas with 5% UHP, the pH is more acidic thus Fe exists as soluble Fe(II). Therefore, percolation rate will be slower with 5% UHP.

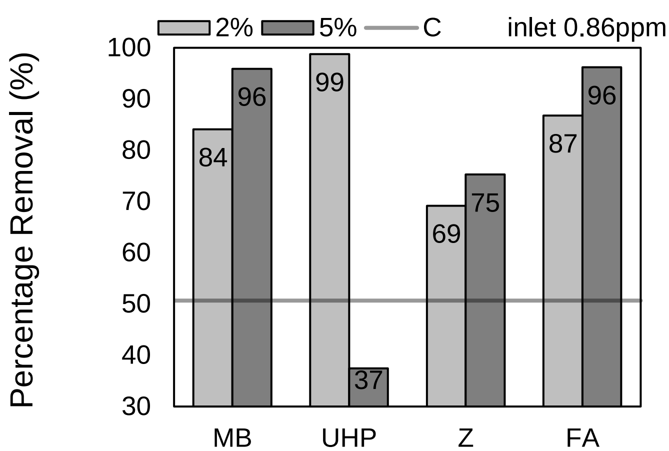


Figure 10: Average percentage removal of Fe(III) in columns with different types and proportions of fine materials.

Among all studied heavy metals in this study, Mn(II) was the most critical one. Figure 11 summarizes the average percentage removal of Mn(II) in columns with different types and portions of fine materials. Except columns with FA all other columns including control columns either leached Mn(II) or showed very low removal efficiency. This is due to the initial content of Mn(II) in the soil media as it has been studied in section 7.1. Since the concentration of Mn(II) in the soil is higher than the incoming stormwater, therefore leaching of Mn(II) occurred. However, columns with FA were able to remove Mn(II) due to the slower infiltration rate that promotes better adsorption of heavy metal ions including Mn(II). Results also showed that increasing the proportion of fine material from 2% to 5% improves the Mn(II) removal in columns Z and FA while it slightly worsened the performance for MB and UHP. Churchman et al. (2016) showed that some Hal including UHP have traces of wickmanite (Mn^{2+} Sn^{4+} $(OH)_6$). Therefore, poorer performance of columns with 5% UHP and MB compared with the ones with 2% UHP and MB could be attributed to this mineral which contributes in Mn(II) leaching.

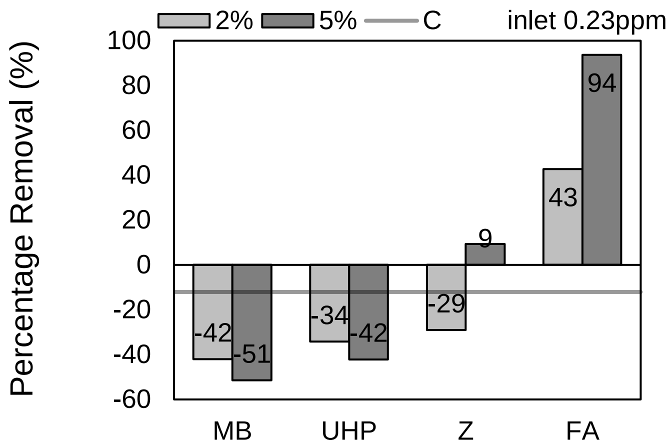


Figure 11: Average percentage removal of Mn(II) in columns with different types and proportions of fine materials.

Table 16 shows the final concentration of heavy metals ions obtained corresponding to the percentage removal. Based on water quality standard of Malaysia (DOE, 2006), there are 3 different classes of water quality related to stormwater including class IIB for recreational body contact, class IV for irrigation, and class V for further treatment. The result obtained in this study showed that all heavy metals concentrations are brought down to class IIB standard except for Mn. MB, UHP, and Z yielded Mn(II) concentration that is categorized in class V where further treatment would be required. Further investigation on Mn(II) leaching showed that the sand material used is rich with Mn(II). However, Mn(II) content will be reduced by frequent flushing of the system with water. Therefore, it is recommended to flush the system with water several rounds before actual usage of it for stormwater treatment. Moreover, infiltrated water from columns with 2% FA is classified as class IV standard that can be used for irrigation purpose while columns with 5% FA was able to treat the stormwater to class IIB standard.

Table 16: Average concentration of heavy metals ions in effluent for different types of filter composition.

Metals ions	Average concentration in effluent (ppm)										
	MB2%	MB5%	UHP2%	UHP5%	Z2%	Z5%	FA 2%	FA 5%	C	Class IIB	Class IV
Zn(II)	0.028	0.026	0.005	0.013	0.007	0.006	0.003	0.001	0.013	2	5
Pb(II)	0.003	0.003	0.002	0.006	0.004	0.004	0.004	0.003	0.005	-	-
Ni(II)	0.004	0.006	0.002	0.001	0.004	0.004	0.002	0.001	0.003	0.05	0.2
Fe(III)	0.137	0.035	0.011	0.538	0.265	0.213	0.114	0.033	0.424	1	5
Mn(II)	0.327	0.348	0.309	0.327	0.297	0.209	0.132	0.014	0.258	0.1	0.2
Cu(II)	0.005	0.005	0.005	0.006	0.006	0.006	0.006	0.007	0.006	0.02	-

Class V

Class IV

Class IIB

Operating pH: 6-7

*Note: Class V water is any concentration higher than class IV water

5.6 Material ranking for selection

As discussed earlier, the filter media for tropical biofiltration application needs to perform well both in pollutant removal and infiltrating water. Therefore, to compare the general performance of 8 different soil compositions (and control columns) of this study, a ranking method is proposed in which a ranking score has been calculated for each composition based on the two criteria: (1) infiltration rate, and (2) pollutant removal. In this approach, the linear transformation of infiltration rate and final effluent concentration for the six heavy metals of this study are individually normalized into the domain of [0, 1] based on their own minimum and maximum measured values according to Van Ooyen and Nienhuis (1992). For infiltration rate, the calculated score is named IR where IR=0 stands for the lowest infiltration rate and IR=1 for the highest one. Similarly, pollutant removal score (PR) is calculated for each heavy metal by Eq. (8)

$PR_x = (1 – NEC_x)$ (8)

Where PR_x is the pollutant removal score for metal x; NEC_x is the normalized effluent concentration of metal *x* (x can be Zn(II), Pb(II), Ni(II), Fe(III), Mn(II), and Cu(II)). NEC_x=0 stands for minimum concentration of metal x in effluent while NEC_x=1 stands for the maximum concentration. Therefore, the best pollutant removal will be scored as PR=1 while the worst will be scored as PR=0. After calculating the IR and PR scores, a weighted average score is calculated by Eq. (9) according to the method adopted from Talei et al. (2010) on comparison study of several hydrological models.

$$R_i = \frac{IR_i + \frac{1}{6}(PR_{Zn} + PR_{Pb} + PR_{Ni} + PR_{Fe} + PR_{Mn} + PR_{Cu})_i}{2} \quad (9)$$

Where R_i is the ranking score of soil composition *i*; IR_i is the infiltration rate score for soil composition *i*; and $(PR_x)_i$ is the pollutant removal score of metal *x* in soil composition *i*. The results of the ranking scores for 9 soil compositions (including the control columns with no fine-grained materials) are presented in Table 17. As can be seen, the highest score is achieved by UHP2% followed by MB2% and control columns (C).

Table 17: Ranking score for infiltration rate (IR), pollutant removal (PR), and overall performance (R) for different soil compositions of this study.

	MB (2%)	**MB (5%)**	**UHP (2%)**	**UHP (5%)**	**Z (2%)**	**Z (5%)**	**FA (2%)**	**FA (5%)**	**C**
IR	0.899	0.544	0.659	0.213	0.375	0.091	0.318	0	1
PR	0.496	0.463	0.795	0.353	0.475	0.541	0.696	0.785	0.376
R	***0.697***	0.504	***0.727***	0.283	0.425	0.316	0.507	0.392	***0.688***

Note: The top three compositions based on R score are highlighted by bold and italic fonts.

CHAPTER 6

VEGETATED COLUMNS STUDY

6.1 Introduction

Based on the finding from Chapter 5, the media structure for control columns was adopted for vegetated columns study. Although structure with 2% UHP showed better overall performance, the improvement was not significant and thus control column media structure was adopted instead. Additionally, to prevent complex correlation between sand, fine-grained materials, and vegetation involved, therefore fine-grained materials were not used in vegetated columns study. This chapter is focused on studying vegetated biofiltration soil columns under tropical condition. The aim of this chapter is to evaluate the performance of selected plants functioning in a biofiltration system through assessment of two criteria of infiltration rate and pollutant removal efficiency. Synthetic stormwater is used in this chapter with additional nutrients pollutant in the form of Total Nitrogen (TN) and Total Phosphorus (TP). The dosage of synthetic stormwater was re-calculated (based on similar method used in Chapter 4) for vegetated columns since the employed column setup have bigger diameter. This dosage was calculated as 13 liters for each simulated event (see Appendix B). As the first step, it was needed to select proper plants from the candidate plants shown in Table 13 (see section 4.9) through observing their behavior during a monitoring stage. Monitoring stage was conducted for 6 months by watering the plants in pots with tap water in the Monash University greenhouse. Based on the plants performance in monitoring stage, specific plant species were selected for each of the non-seasonal and seasonal studies. After that, selected plants were transferred to the biofiltration columns to introduce adaptation period for 2 weeks by undergoing daily watering with synthetic stormwater.

6.2 Plants Monitoring, Survivability, and Selection

Following the monitoring procedure discussed in section 4.9, all plants were watered with 300 ml water twice a day for the first 2 weeks. After that, the watering frequency was reduced to once a day with the same volume of 300 ml for each potted plant. During the first few months of monitoring period, few plants showed significant stresses as summarized in Table 18. *Cymbopogon nardus* (CN) and *Hibiscus rosa-sinensis* (HR) were dried up after 4 months due to the high temperature observed in the greenhouse period March – July 2015, despite proper air circulation and minimum heat retained. According to Fern (2014), these plants would grow best in the temperature range of 20-30 ^oC. Although the average temperature in Malaysia is 28-32 ^oC all year round, however Malaysia experiences temperature range of 32-33 ^oC during dry period (April – October) (Lim and Samah, 2004). Moreover, since the plants are kept in the greenhouse, additional increase in temperature is inevitable. Therefore, it was concluded that these two plants could not survive for biofiltration system in tropical conditions for a long run. On the other hand, *Iris pseudacorus* (IP) found to be attractive for grasshoppers as it was frequently eaten by them. However, this plant showed quite good growth in the first few weeks. Eventually, the plant could not survive from frequent insects' attack and died. Since all plants were in the same condition and environment, it was considered as a drawback for this specific plant.

Despite the failure of the above mentioned three plants, the other seven plants could survive throughout the monitoring period. These plants were *Pedilanthus tithymaloides* (PT), *Heliconia psittacorum* (HP), *Hymenocallis speciose* (HS), *Cordyline fruticosa* (CF), *Graptophyllum pictum* (GP), *Cyperus alternifolius* (CA), and *Bambusoideae* (BE). However, few noticeable observations were found: Plant PT, HP, and HS stopped growing once the watering frequency was reduced from twice a day to once. In addition, flowers were not blooming although the leaves and stems were not dry. This observation continued throughout the monitoring stage (6 months). Plant BE showed sensitivity to weather condition as it was getting stressed in dry weather (no rain days) where all its leaves were turning to reddish color. However, during rainy period, it was able to recover fast and turn the leaves to greenish color. Plants CF, GP, and CA did not show any symptoms during monitoring stage despite of the reduction in watering frequency and the exposure to various weather conditions.

Table 18: Summary of plants monitoring and selection

Plant name	Observation	Selection
Cymbopogon nardus	- Dried after 4 months	Not included
Hibiscus rosa-sinensis	- Dried after 4 months	Not included
Iris pseudacorus	- Dead from insects' attack	Not included
Bambusoideae	- Reddish leaves during hot days - Fast recovery after rainfall	Seasonal study
Cordyline fruticosa	- Fast leaves regeneration - No stress observed	Seasonal study
Cyperus alternifolius	- Fast growth rate - No stress observed - Regular trimming needed	Seasonal study
Graptophyllum pictum	- Plant grew steadily - Wilted leaves during hot days	Seasonal study
Heliconia psittacorum	- Survived - Stopped growing after 2 weeks - Flowers did not bloom after 4 weeks	Non-seasonal study
Hymenocallis speciosa	- Survived - Stopped growing after 2 weeks - Less flowers bloom after 2 weeks	Non-seasonal study
Pedilanthus tithymaloides	- Survived - Stopped growing after 2 weeks	Non-seasonal study

Based on the observation on the ten selected plants species, it was concluded that 3 candidate plants including CN, HR, and IP should be excluded due to their poor performance. Although plants PT, HP, and HS showed stress symptoms, they were included in the columns study to further investigate their survivability as well as performance in the biofiltration system for both hydrologic and pollutants removal efficiency. However, understanding that plants PT, HP, and HS were sensitive to drought, only a non-seasonal study was conducted on these 3 plants. On the other hand, plants CF, GP, CA, and BE were considered for further investigation under seasonal condition. Among these 4, plant BE which showed more sensitivity to weather condition compared to the other 3 was selected for the survivability study as well.

6.3 Non-Seasonal Vegetated Columns Study

As it was mentioned in Section 6.2, PT, HP, and HS were selected for non-seasonal condition due to their sensitivity to drought. In this non-seasonal study, the vegetated columns were watered with gap of 3 dry days. Although the study was conducted similarly and at the same time for the 3 selected plants, the duration of the experiment was varied due to some issues including plants survivability and clogging of the system.

6.3.1 Plants Survivability for Non-Seasonal Columns Study

After the plants were transferred into soil columns, observation on the plants behavior were conducted to investigate their adaptability in the new environment. As it has been described in section 4.9, the columns were watered daily with synthetic stormwater during adaptation stage for 2 weeks to aid plant's survivability. After that, weekly sampling and testing was conducted for both water quality and infiltration rate for the period of 5 months to observe the performance and behavior of the vegetated columns. However, it was noted that plant behavior study was conducted based on daily physical observation only since variables such as root length could not be measured to avoid disturbance to the system.

Figure 12 shows the PT plants after they have been transferred to the soil columns. It could be seen (compare Figure 12(a) and (b)) that the plants were showing some stresses for the first few days where the leaves were turned yellow and fell rapidly. After 8 days, almost all yellow leaves fell, yet the branches were not dried up and instead started to grow few new leaves. At day 20, more new leaves were grown, and flowers were blooming. Therefore, it was concluded that the plants could adapt well to the new environment and were ready for being tested. However, after 5 months of testing and observation (with total of 16 testing sessions), the leaves slowly fell, and the plants started to dry up as shown in Figure 12(d). Therefore, it was concluded that the plants could not survive in a long period of exposure to polluted stormwater.

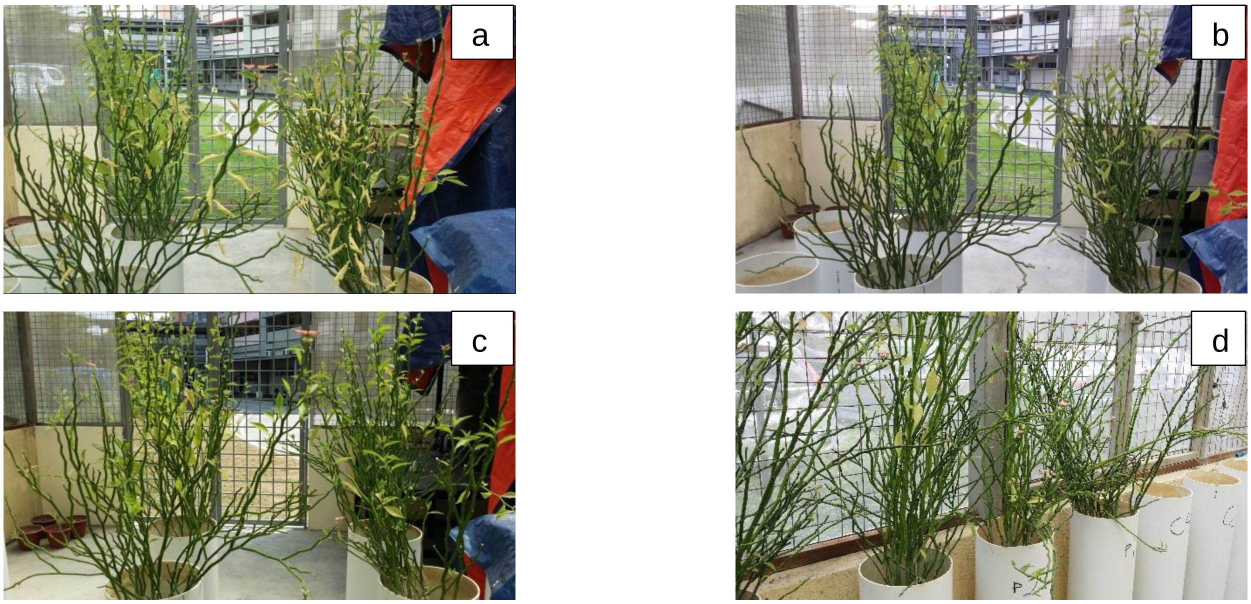


Figure 12: *Pedilanthus tithymaloides* after transferred to soil columns
a) day 5, b) day 8, c) day 20, d) day 150.

In comparison with plant PT, plant HP was not able to perform for the full experiment duration of 5 months. One of the major concern was the fact that the plants showed some illness soon after being dosed by synthetic stormwater which could be possibly linked to the presence of pollutants. It was evident that the plants were constantly under stress throughout the experiment. The physical respond shown by this plant are presented in Figure 13. Just two weeks after starting the testing, many of the leaves turned to yellowish color and red dots kept increasing on the leaves surfaces. These burn marks were started from the tip of the leaves and spread to the body of them. According to a study on plant stress by Peet (1997), such symptoms can occur due to the excess salts and nutrients in the water (i.e. synthetic stormwater in the present case). Author also mentioned that the excess salts and nutrients is likely to damage the plant root as well. After 60 days of observation, the plant started to dry up; therefore, testing was no longer continued. Until this point, total of 7 testing sessions were completed for plant HP. Considering survivability requirement, plant HP was found as an unsuitable plant for being used in biofiltration system due to its health failure under polluted environment.

Figure 13: Red dots on *Heliconia psittacorum* leaves after 14 days of plant's transfer.

Plant HS showed a very promising observation during the first 2 weeks after plant's transfer to the columns. The only physical respond shown by the plant was the yellowish dried leaves which is common when plant environment is changed (See Figure 14(a) and (b)). One of the observations during the monitoring stage of this plant (being in standard pots in green house) was blooming flowers once in every 2-3 weeks. However, even after few weeks of transferring the plant into the soil-column systems, no flower blooming was observed as shown in Figure 14(c). According to Chapin (1991), one of the major reason for such behavior in this plant could be the nutrient imbalance. The concentration of dosed nitrogen and phosphorus in stormwater has been perhaps not suitable for this plant. However, the experimental study was continued with watering and testing of the system. After 4 successful testing, plant HS started to dry up and the same burnt marks as plant HP were observed; thus, the testing was no longer continued. Figure 14(d) shows the plant’s condition after 40 days since the transfer. Considering survivability requirement, it was concluded that plant HS is not suitable for biofiltration system due to its sensitivity to polluted water, similar to plant HP.

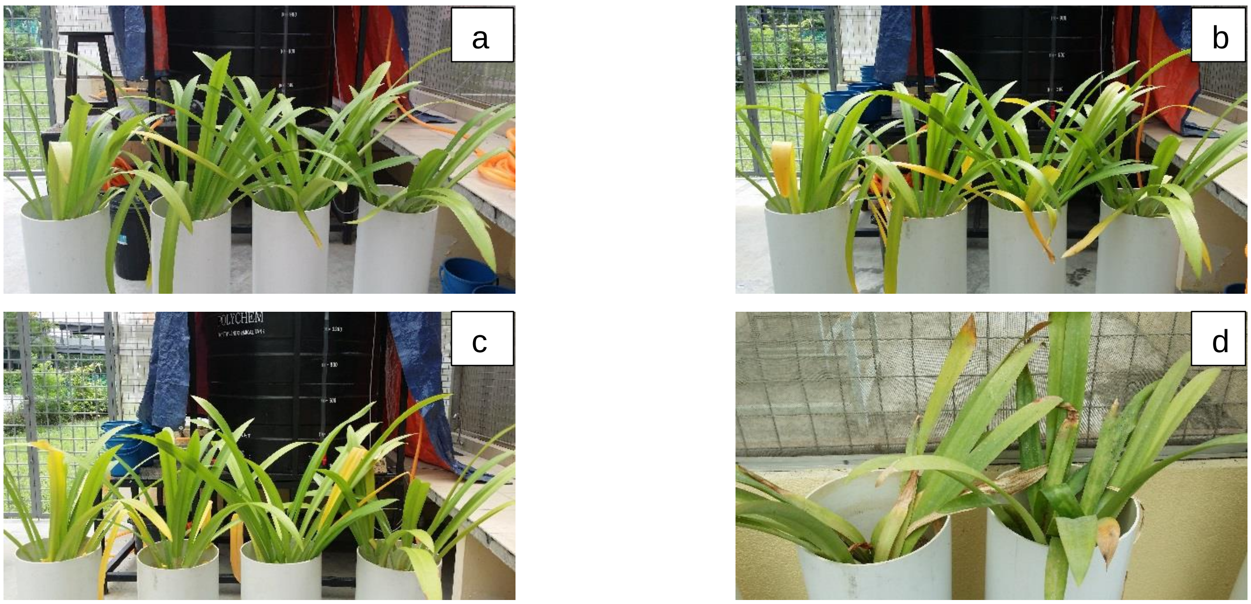


Figure 14: *Hymenocallis speciosa* after transferred to soil columns
a) day 1, b) day 5, c) day 14, d) day 40.

6.3.2 Infiltration Rate in Non-Seasonal Columns Study

Columns were watered prior to infiltration rate measurement to ensure the fully saturation condition in the soil media. Once steady flow was achieved and no air bubble from the soil voids appeared on the water surface, the measurement was conducted following the constant head method (ASTM D2434-68, 2006). The data obtained from the measurement was then translated into infiltration rate value by using Eq. (3). The average value of the 4 replicates columns were then calculated to produce a data point.

Infiltration rate measurement on plant PT was done on 16 different testing dates within 5 months of experimental period. As it can be observed in Figure 15, the columns with plant PT had an initial infiltration rate of 259 mm/hr. The infiltration rate of plant PT shows an overall decreasing trend while fluctuations were detected during the experiment period. This decreasing trend was due to the clogging that naturally occurs in the biofiltration system, while the fluctuations were attributed to the root growth of the plant. As it was mentioned in section 2.2.6, the penetration of the plant's root creates pores inside the filter media which can contribute to some changes in infiltration rate which could be the source of those observed fluctuations. This was proven by comparing the infiltration rate values with control columns (see Figure 15) where the infiltration rate of control columns kept decreasing consistently for 5 months of experimental period. After 5 months of experiment, the final value of infiltration rate for plant PT was 191 mm/hr. Notable drop of infiltration rate value was observed during the first week of experiment. The value drop was attributed to the self-compaction of the filter media due to the watering.

Infiltration rate test for plant HP was done on 7 different sessions for 2 months period. As it can be seen in Figure 15, the initial and final infiltration rate values for columns with plant HP are 361 mm/hr and 330 mm/hr, respectively. In general, the average infiltration rate was higher than the ones obtained for plant PT due to the difference in root structure. Based on the observation during plant's transfer, plant PT has thinner root system compared with plant HP. Therefore, root penetration in the columns with plant PT would create smaller pores compared with the root penetration of plant HP. Since the system pores determine the flow of the infiltrated water, infiltration rate of plant HP was faster than plant PT. However, it is believed that the fast infiltration rate has contributed to the poor survivability rate of plant HP in the system. Since incoming water has been drained faster, the system has experienced a longer dry period compared to HP columns; thus, the survivability of the plants was affected.

The infiltration rate test for plant HS was conducted for 4 sessions during 1 month of experiment and the results are presented in Figure 15. As it can be seen, the infiltration rate value dropped from 361 mm/hr to 322 mm/hr. Although the infiltration rate values for plant HS were similar to plant HP, it resulted differently in terms of survivability. This could be attributed to reasons such as plant size and root growth. Plant size determines the amount of water and nutrient uptake which would affect its survivability. On the other hand, root growth affects the water pathway or infiltration rate in the system.

The values of infiltration rate for vegetated columns were compared with the ones from control column (with no vegetation). It was found that the infiltration rate values of vegetated columns are generally higher compared to the ones obtained from control columns (as shown in Figure 15). Since vegetated columns showed stability in infiltration rate value compared with control columns, this confirms the advantage of using plants in biofiltration system and its role in the recovery of infiltration rate values (Siriwardene et al., 2007; Le Coustumer et al., 2012). In other words, clogging, as a common issue related to the biofiltration systems, could be reduced by selecting appropriate plants. In comparison with the infiltration rate value recommended by guidelines, plant PT fulfill the requirement as the infiltration rate value is averaging between 150-200 mm/hr (FAWB, 2009; MSMA, 2012). Based on this study, plants with thinner root (PT) would produce lower infiltration rate value compared to the ones with thick roots (HP and HS). In addition, fast infiltration rate could potentially affect the survivability of the plants due to the low retention time of the infiltrated water.

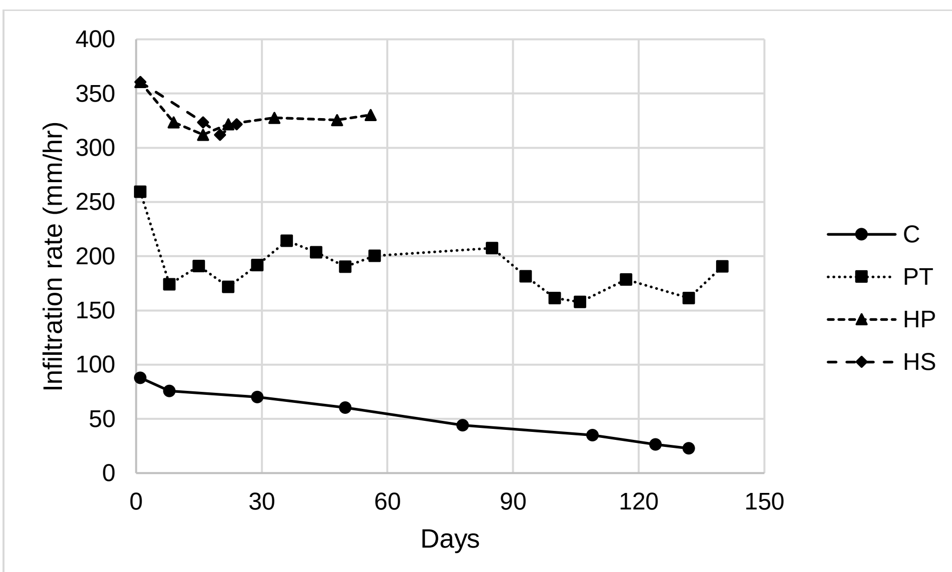


Figure 15: Infiltration rate values in non-seasonal study.

6.3.3 Pollutant Removal in Non-Seasonal Columns Study

Along with infiltration rate test, pollutant removal test was carried out during the same time frame. In total, 16, 7, and 4 tests were conducted over the experimental period for plant PT, HP, and HS, respectively. It is noted that all tests were conducted when all plants were still healthy. Figure 16 presents the box plots of heavy metal removal efficiencies (each data is the average value resulted from 4 column replicates). As it can be seen, the removal of Cu(II) and Ni(II) ions were stable for all plants with the rates higher than 90%. However, a discrepancy was observed in Zn(II) and Pb(II) removal for plant PT. This was attributed to the longer experimental duration conducted on plant PT. It was expected that a long exposure of the system to experiment may show a gradual reduction of efficiency due to potential soil saturation with pollutants. However, looking into the performance of all plants in removing Mn(II) and Fe(III), unstable removal rate was observed. This is due to the presence of corresponding metal ions in the soil media. To prove this reasoning, a short study on initial metals concentration in the soil media was conducted and discussed in section 7.1. It is worth mentioning that although plants HP and HS were under constant stress throughout the experiment, this stress has not affected the performance of pollutants removal until the point where the plants were healthy (not dried yet).

The boxplots for nutrients removal can be seen in Figure 17. In general, the percentage removal of TN and TP are higher in columns with plants compared to control columns. This shows the effect of plants for nutrient adsorption. Although plant PT, HP, and HS showed an improvement for nutrient removal, there was a large range of TN percentage removal observed especially in plant PT (from -1.27% to 54.90%) (see Figure 17). This indicates the possible instability in TN removal that could be attributed to the fact that the accumulated TN in soil (excess to need of plants) is generally flushed out during the next watering session.

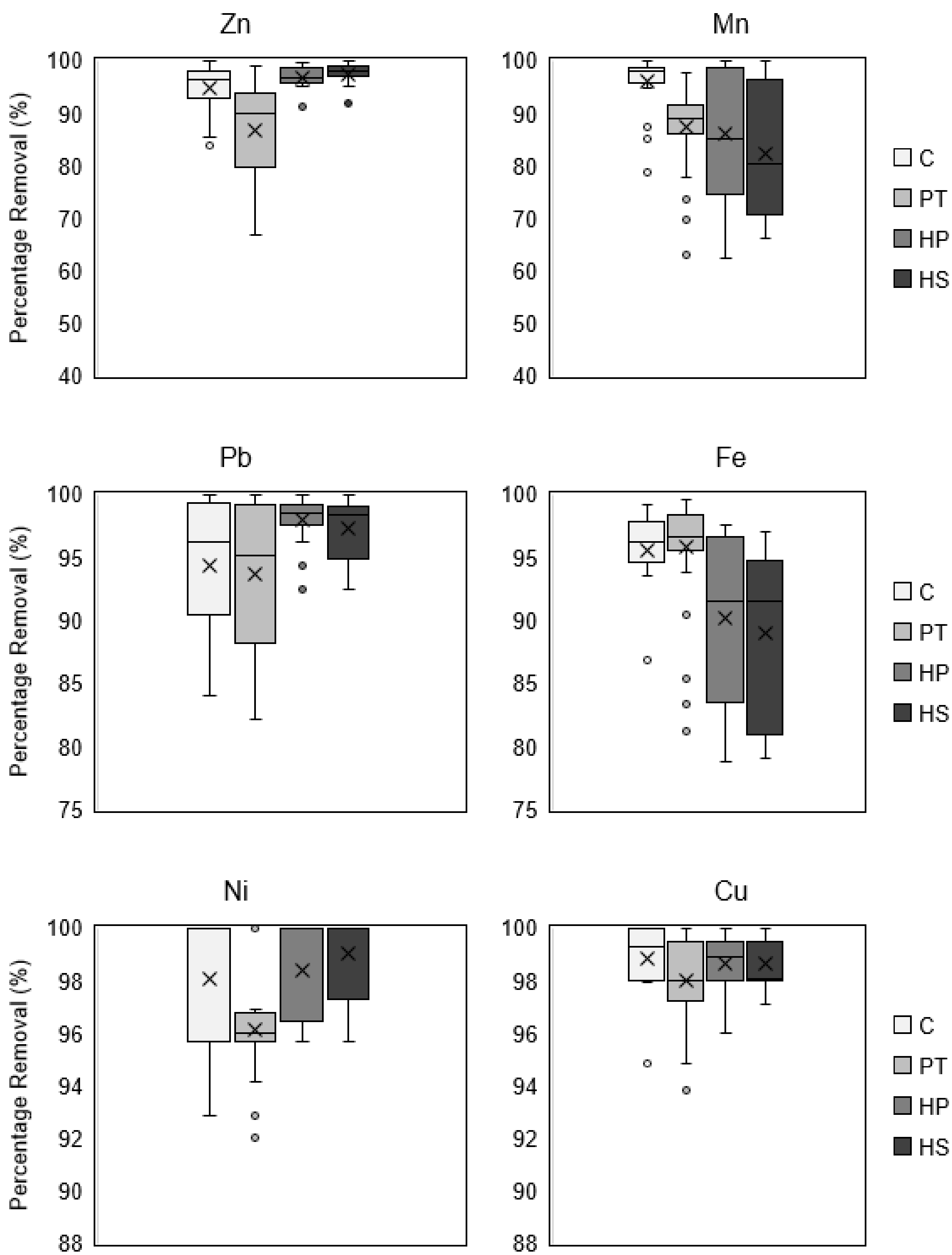


Figure 16: Box plots for heavy metals removal efficiency in non-seasonal columns study.

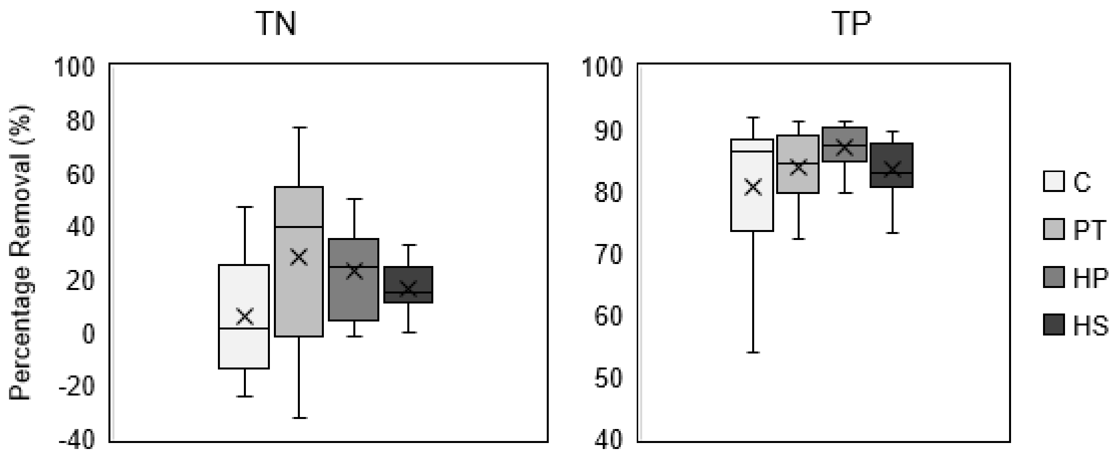


Figure 17: Box plots for nutrients removal efficiency in non-seasonal columns study.

The average of percentage removals of all pollutants is provided in Table 19. It can be seen that the heavy metals removal does not change significantly with the using vegetation, except for Mn(II) and Fe(III) in plant HS. As it has been mentioned, the initial presence of Mn(II) and Fe(III) in the soil media caused the spike of these metals ions concentration. Since plant HS dried up fast, the wash out process of Mn(II) and Fe(III) has been progressed partially; thus reduction in removal percentage was evident. On the other hand, the effect of vegetation can be observed clearly for nutrients removal, especially TN. Table 19 shows that adding plants PT, HP, and HS can improve TN removal by 23.30%, 16.88%, and 10.20%, respectively. In comparison, a nutrients removal study of bioretention in Singapore by Wang et al. (2017a) showed TN removal of 25% with TN inlet concentration of 2.45 ppm. In this study, the removal of TN brought the concentration of TN from class V to class IV water which can be used for irrigation purpose. For TP removal, adding plants PT, HP and HS could improve the performance by 3.43%, 6.44%, and 3.02%, respectively. Although the TP removal improvement was not significant in percentage, it was considered as an evident of advantageous use of plants due to the fact that the outlet TP concentration in vegetated columns falls in class IIB while it is in class IV for control columns. Overall, it was concluded that vegetated columns (with plants PT, HP, and HS) generally can enhance the pollutants removal efficiency.

Table 19: Pollutant removal efficiency for non-seasonal columns study.

	Zn(II)	Pb(II)	Ni(II)	Fe(III)	Mn(II)	Cu(II)	TN	TP
Synthetic stormwater								
Inlet concentration (ppm)	0.250	0.140	0.030	0.860	0.230	0.150	4.32	1.12
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class V	Class IV	Class V	Class IV
Column C								
Avg. removal (%)	94.77	94.38	98.08	95.61	95.94	98.81	6.52	80.51
Avg. outlet concentration (ppm)	0.013	0.008	0.001	0.038	0.009	0.002	4.03	0.22
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IV
Column PT								
Avg. removal (%)	86.65	93.17	96.16	95.88	87.48	98.01	28.82	83.94
Avg. outlet concentration (ppm)	0.033	0.010	0.001	0.035	0.029	0.003	3.07	0.18
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IIB
Column HP								
Avg. removal (%)	96.82	97.98	98.39	90.15	86.01	98.62	23.40	86.95
Avg. outlet concentration (ppm)	0.008	0.003	0.001	0.085	0.032	0.002	3.31	0.15
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IIB
Column HS								
Avg. removal (%)	96.38	97.37	99.04	75.70	47.12	98.64	16.72	83.53
Avg. outlet concentration (ppm)	0.007	0.002	0.001	0.137	0.108	0.001	3.59	0.18
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IIB	Class IV	Class IIB

*Operating pH: 6-7

6.4 Seasonal Study on Tropical Vegetated Soil Columns

Based on the observation during monitoring stage, four plant species were considered for this seasonal study including CF, GP, CA, and BE due to their relative better performance compared to the others. In the seasonal study, the sampling and testing was predetermined to simulate both wet and dry seasons. There were 10 sampling sessions in total including 5 wet and 5 dry simulations. During the wet season simulation, watering frequency with 0, 0, 1, 2, and 3 days gap was adopted. On the other hand, dry season simulation was implemented with 5, 7, 10, 14, and 21 dry days gap. Overall, the experiment lasted for 73 days.

6.4.1 Plants Survivability for Seasonal Columns Study

The four plants of this study (i.e. CF, GP, CA, and BE) could survive well during both wet and dry conditions (See Figure 18(a-d)). Figure 18(e-h) show the root structure and the growing patterns for each plant. CF has a thick, firm root which does not grow vertically while GP has a thin soft root which does not grow vertically as well. However, CA with a thick root tends to grow vertically (Cui et al., 2009). On the other hand, BE has thin root that grows mainly in vertical direction.

Plant CF started to experience falling leaves after 25 days from the starting date of the experiment where the plants were under the 10 dry days gap experience. By day 75, after the lengthy 3-weeks of dry days, more falling leaves were observed. Although the submerged zone was present to allow plant roots absorb water, the roots could not penetrate deep enough to reach the submerged zone during the dry period. Table 20 summarizes the root length of each plant species in this seasonal study. The initial depth of CF root was about 15 cm (see Figure 18(e)) while after 25 days of experiment the root grew to 20 cm. It is noted that the measurement on root growth on all plants was done through the observation on two transparent columns (as part of the four replicates). Further observation in transparent columns showed that the CF root growth for the next 50 days of the experiment was not considerable and didn’t help the plant to reach the submerged zone. However, CF could survive and maintain its form without showing any disease throughout the experiment.

On the other hand, plant GP only showed stress symptom towards the end of experiment when the 21 dry days gap was introduced. Plant GP started to wilt and have falling leaves. Plants normally wilt mostly because of water shortage. Similar to plant CF, the water level in the submerged zone did not decrease even during the long dry days period. It was also observed that the root growth of GP only happened horizontally to encircle the column. The initial depth of GP root was 10 cm (see Figure 18(f)) while the root grew to 15 cm after 25 days of experiment. However, further observation showed that GP root did not have any noticeable vertical growth. This resulted in less water absorption from submerged zone which caused wilting and falling leaves. However, this plant could survive even during the 21 dry days period.

Figure 18. Selected plants species for seasonal study and their root structures. (a) *Cordyline fruticosa* (b) *Graptophyllum pictum* (c) *Cyperus alternifolius* (d) *Bambusoideae* (e) Root structure of *Cordyline fruticosa* (f) Root structure of *Graptophyllum pictum* (g) Root structure of *Cyperus alternifolius* (h) Root structure of *Bambusoideae.*

It was quite surprising to see that plant CA did not show any stresses symptom throughout the experimental period. Rather, plant CA showed a significant growth rate especially when the number of stems was increased and the plants grew taller. Since the root of CA grows vertically, it was concluded that the plant root growth plays a key role in plants survivability. The initial depth of CA root was only 10 cm (see Figure 18(g)) while by the day 25th it was about 40 cm. This rate of root growth was progressive, and the CA root was able to reach the bottom of the columns (i.e. the root depth reached 70 cm) by the end of the experiment at day 75. During the 21 dry days period, only few leaves of CA plant showed stresses and turned to yellowish color. The deep root penetration of CA plant allowed absorption of water from submerged zone during dry period. This was evident as the water level of the submerged zone started to fall after day 25 where the dry period was started to be introduced. It is worth mentioning that care has been taken to return water level of submerged zone to its original one before measuring infiltration rate as the value of infiltration rate is a function of existing water head.

BE was introduced as a sensitive plant due to its fast drying and recovering depending on the weather condition and watering frequency. During the experiment period, no stresses symptom was observed. On the other hand, the plants did not dry as fast as before when it was planted in pot. It is believed that a better vertical root growth in columns compared to the pots allow the plants to reach submerged zone and fulfill their water demand during dry period. The length of the root for plant BE grew from 15 cm to 40 cm by the end of the experiment. Since the filter media was 400 mm, therefore the plant root could reach the submerged zone level.

Table 20: Vertical root length for each plant in seasonal study

Plants	**Vertical root penetration since establishment (cm)**	
	Day 1	Day 75
Cordyline fruticose **(CF)**	15	20
Graptophyllum pictum **(GP)**	10	15
Cyperus alternifolius **(CA)**	10	70
Bambusoideae **(BE)**	15	40

6.4.2 Infiltration Rate on Seasonal Columns Study

Infiltration rate test was conducted 6 times from which 2 tests were conducted during wet season simulation (0 and 2 days gap) and another 4 tests were during the dry season simulation (7, 10, 14, and 21 dry days). The procedures for infiltration rate measurement were in accordance with the standard method (ASTM D2434-68, 2006). The values of infiltration rate for the four plants of this study are presented in Figure 19. As it can be seen in Figure 19, infiltration rate for CF started at 728 mm/hr and ended at 710 mm/hr. After 15 days of experiment which was during the wet season simulation, a drop in the infiltration rate was observed (down to 649 mm/hr). This could be due to the frequent watering of the system and the potential resulted segregation of the particles. However, entering to the dry period simulation with 5 dry days gap, the value of infiltration rate increased and was then stabilized. Overall, there was no significant decrease in infiltration rate even after more than 70 days of experiment. The fibrous root structure of this plant creates high number of pores in the filter media which provide pathways for water to infiltrate through the media. However, the CF root tends to grow mainly horizontally with a low grow rate. Thus, infiltration rate of CF columns was not affected in the long run and became almost stable.

Similar trend was obtained for GP columns with lower overall infiltration rate. There was not any significant difference between the initial and the final value of infiltration rate. Increment of infiltration rate from 520 mm/hr to 530 mm/hr was observed at the end of the experiment. Columns of GP showed a lower infiltration rate value compared to the columns of CF due to the difference in root structure. The thin soft root from GP could not contribute much in creating additional pores compared with thick and firm root of CF. Similar to CF, GP root does not grow vertically, and the root growth rate is also not high. Therefore, the infiltration rate of GP columns became stable in the long run as well.

On the other hand, a decreasing trend in the infiltration rate value for CA columns was observed from 661 mm/hr to 402 mm/hr before bounced back to 465 mm/hr at the end of the experiment. Since infiltration rate is highly related to the plant root growth, it was expected to see an increase in infiltration rate due to the root penetration in the system (Le Coustumer et al., 2012). However, as mentioned in section 6.4.1, CA showed a massive vertical root growth that may cause soil compaction. Such compaction would eventually be the cause of reduction in infiltration rate. At the end of the experiment, a slight increase of infiltration rate value was observed. This is attributed to the long dry period of 21 days in which cracks in soil could naturally increase and provide pathways for water through the system which in turn gives a bit of increase in infiltration rate.

Infiltration rate value for BE columns was constantly decreasing from 782 mm/hr to 520 mm/hr at the end of the experiment. Similar to CA, BE had a massive vertical root growth that could have caused soil compaction. There was a slight increase of infiltration rate value from 530 mm/hr to 563 mm/hr during 14 dry days gap which is attributed to the soil cracks. However, with introduction of 21 dry days gap, the infiltration rate dropped to 520 mm/hr due to the massive growth of the plants root. Since BE has thinner root structure compared to CA, the cracks created during the dry period could be filled with BE roots; thus, a reduction in infiltration rate has occurred. Table 21 summarizes the infiltration rate value for the seasonal vegetated columns study.

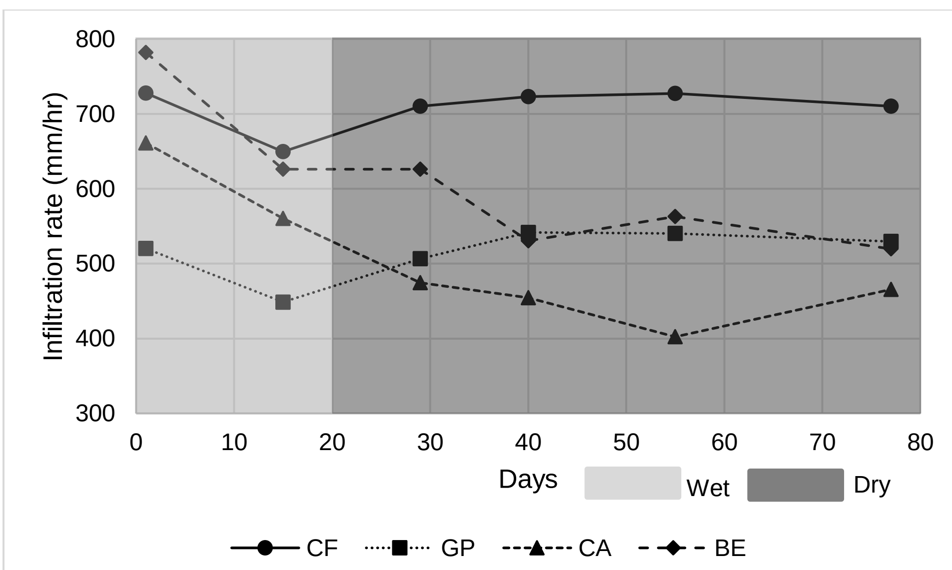


Figure 19: Infiltration rate values in seasonal columns study

Table 21. Infiltration rate value (mm/hr) for seasonal vegetated columns study

Days	1	15	29	40	55	77
CF	728	649	710	723	727	710
GP	520	449	507	542	540	530
CA	661	560	475	454	402	466
BE	782	626	626	530	563	520

6.4.3 Total Nitrogen (TN) Removal on Seasonal Columns Study

Figure 20 shows the change in effluent's TN concentration for the 10 sessions of experiment. All plants showed a similar pattern although their individual values were different. Within the first 25 days of the experiment, it is noticeable that TN concentration in the effluent have increased from 3.30, 3.93, 1.93, and 3.53 ppm to 4.20, 4.18, 3.40, and 3.70 ppm for CF, GP, CA, and BE plants, respectively. Soil media naturally cannot contribute much to removing TN (see 6.3.3); therefore, only plants with their nutrients uptake (as part of their growth requirement) can help (Read et al., 2008). During the wet season, the TN concentration shows an increasing pattern (see wet section in Figure 20). This can be attributed to the fact that excess nutrients coming from the synthetic stormwater is more than the required values for plants growth. That's why plants contribution to TN removal is not significant in this period. However, during the dry season, the plants started to get thirsty for both water and nutrients; therefore, more TN is up taken by plants which cause the decreasing trend in effluent TN concentrations (see dry section in Figure 20). When the plants were exposed to more than 15 days of dry period (note that sampling 9 was at 14 dry days and sampling 10 was at 21 dry days), they started to show some stresses symptoms such as rapid falling of leaves and wilting. Therefore, the slight increasing value of TN at day 73 for CF, GP, and CA can be attributed to the less leaves presence, implying the lesser amount of nutrients demand needed by the plants. However, BE columns did not show any stress symptoms and continue to have their natural massive growth. This could be attributed to the fact that BE is considered as a member of grass family with a natural tendency of surviving in various environments. Therefore, with the continuous growing of BE in the columns and the increasing need for nutrients, the TN concentration kept decreasing even after 21 dry days gap.

Moreover, Figure 20 also shows the difference in TN removal performance for different plants of this study. It can be seen that CA shows an overall lower TN concentration in comparison with CF, GP, and BE. This could be attributed to the higher vertical growth of roots in CA compared to the other plants. Deeper root in CA helps this plant have a better nutrient absorption compared to the other plants with horizontal growth. This finding is supported by Näsholm et al. (2009) study in which it was found nitrogen absorption is mainly by plant roots before moving towards the shoots. Although BE has a vertical root growth as well, the effluent concentration of TN was generally higher than CA columns. This was attributed to the fact that BE, as a member of grass family, does not need high amount of TN to survive and grow (Ozawa et al., 2001); thus, more TN was washed off from the system.

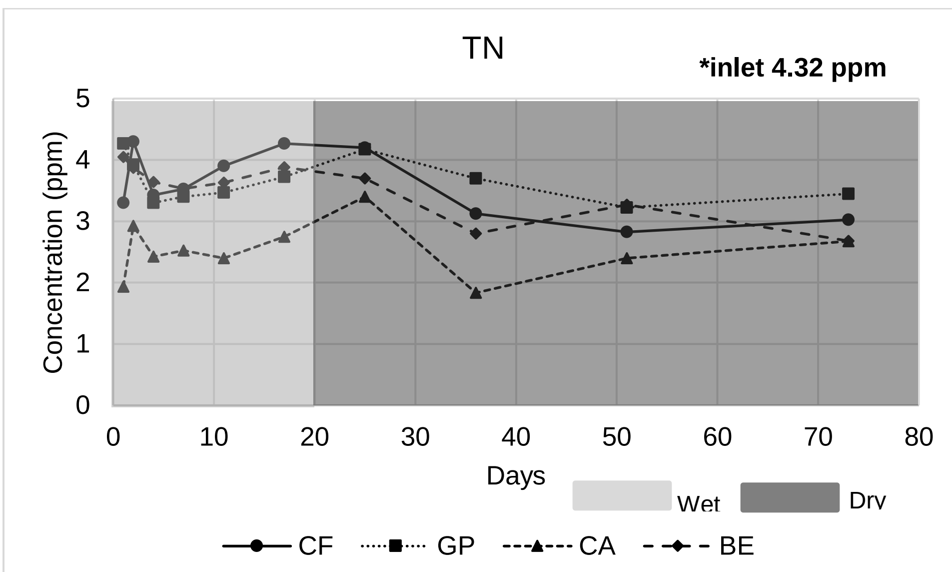


Figure 20: Outlet TN concentration for each plant columns in seasonal study.

6.4.4 Total Phosphorus (TP) Removal on Seasonal Columns Study

The performance of each plant for removing phosphorus is shown in Figure 21. It is evident that the biofiltration system has successfully removed TP by rate of 82-94%

and has brought down its concentration to < 0.2 ppm. This is even better than the control columns in which TP removal was 80.51% (see Table 19). There are few previous studies which produced similar finding. Hsieh et al. (2007a) concluded that standard biofiltration columns could remove phosphorus from 67 to 98% without the aids from any vegetation. Moreover, Zhang et al. (2008b) reported that for sand with phosphorus-rich content, 5% fly ash could improve the phosphorus removal from 2% to 85% without any vegetation. In this study, the presence of vegetation shows an improvement in phosphorus removal. However, the improvement was not significant compared with non-vegetated biofiltration system. In addition, there was no change in the performance of columns during wet and dry seasons. However, BE columns showed constant increasing pattern of TP concentration over the experimental period (see Figure 21). Similar to TN removal, BE was not found to be in need for high amount of nutrients (TP in this case); therefore, relatively lesser TP has been adsorbed by BE plants.

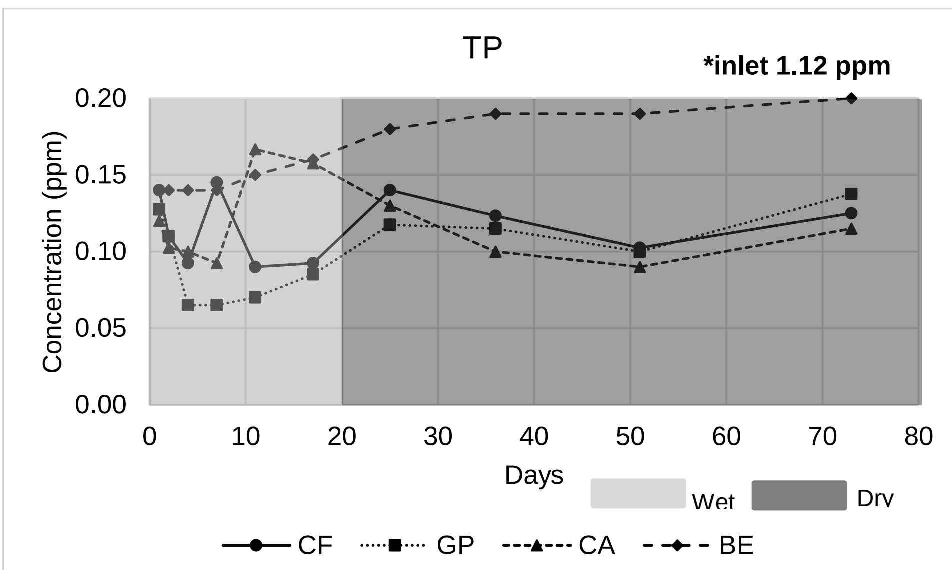
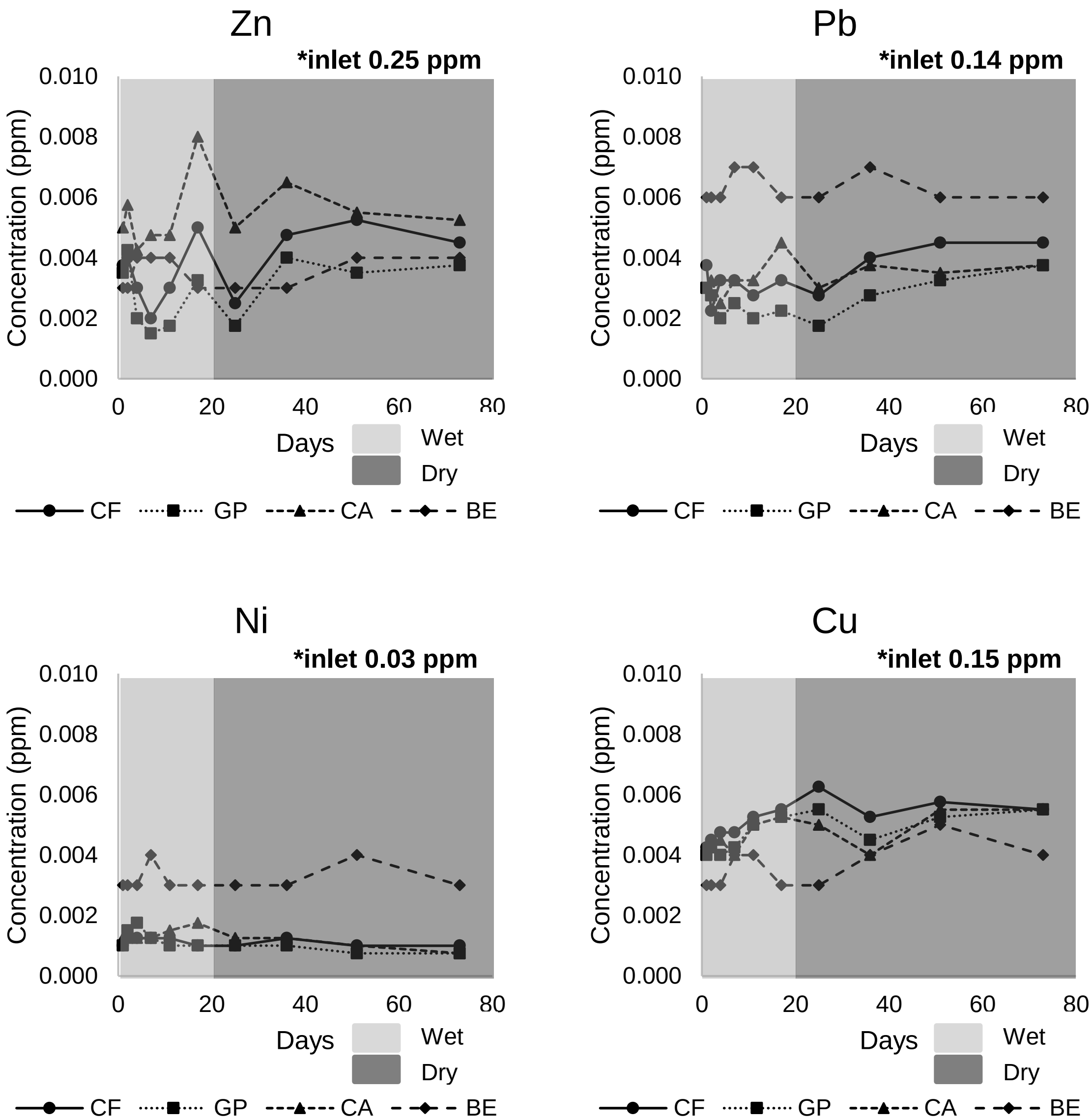


Figure 21: Outlet TP concentration for each plant columns in seasonal study.

6.4.5 Heavy Metals Removal on Seasonal Columns Study

The results of heavy metals removal are presented in Figure 22. All four plants of this study could remove Zn(II), Pb(II), Ni(II), and Cu(II) to the concentrations below 0.01 ppm (or > 95% removal efficiency). This finding is also confirmed by other studies (Blecken et al., 2009b; Reddy et al., 2014b; Lim et al., 2015). However, reported findings on Fe(III) and Mn(II) removal by biofiltration systems are not really consistent. In this study, Fe(III) concentration had an increasing trend throughout the whole experiment (see Figure 22) for the CF, GP, and BE columns. CF with higher infiltration rate compared to GP (see Figure 19) shows lower performance in removing Fe(III) as Fe(III) concentration in CF is consistently higher than the ones in GP. This is consistent with FAWB (2009) where pollutants removal efficiency, especially heavy metals is increased while infiltration rate is decreased. Similar negative correlation between infiltration rate and Fe(III) removal efficiency was found for BE columns as well. However, Fe(III) removal trend in CA was totally different as it can be seen in Figure 22. There is an increasing trend in Fe concentration from day 1 to 25 while the trend becomes decreasing after day 25 to day 51. The infiltration rate for CA columns was decreasing during the experiment with a slight increase at the last sampling round. This was attributed to the aggressive growth of roots and the potential soil compaction in the system. Therefore, Fe(III) removal is also following the infiltration rate trend as they are linked. The significant drop in infiltration rate of CA columns during dry period has caused an improvement in Fe(III) removal as Fe(III) concentrations are reduced during that period. At the last sampling point, however, a long dry period which may have caused cracks in the soil media slightly increases the infiltration rate which in turn reduces the system efficiency in removing Fe(III). Some studies have also shown that in general plant roots are good in Fe(III) uptake (Morrissey and Guerinot, 2009). Therefore, the reduction of Fe(III) concentration in the dry period can also be attributed to the aggressive growth of plant (to reach deeper water) and its potential higher Fe(III) uptake during this period.

Mn(II) concentration in all four types of plants was continuously decreasing until the end of the experiment as the Mn(II) concentration dropped from initial values of 0.100, 0.122, 0.106, and 0.142 ppm to final values of 0.005, 0.006, 0.069, and 0.008 ppm for CF, GP, CA, and BE, respectively. The gradual improvement of Mn(II) removal in the system could be related to the fact that sand is generally rich in Mn(II) and can easily leach it out to water as it flows out from the system. To prove this argument, a study on initial metals concentration in soil was conducted which is discussed in section 7.1.


Zn
*inlet 0.25 ppm
Pb
*inlet 0.14 ppm
Ni
*inlet 0.03 ppm
Cu
*inlet 0.15 ppm
Concentration (ppm)
0.000
0.002
0.004
0.006
0.008
0.010
0
20
40
60
80
Days
Wet
Dry
CF
GP
CA
BE

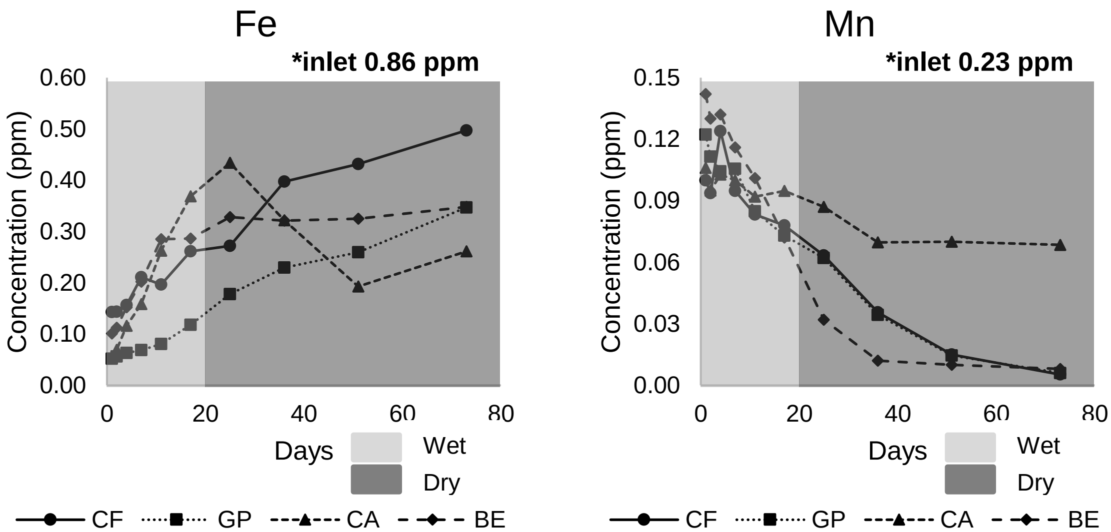


Figure 22: Outlet heavy metals concentration for each plant columns in seasonal study.

6.4.6 Assessment of System Performance in Seasonal Columns Study

Table 22 summarizes the influent and effluent pollutants concentration during the experimental period. Malaysia discharge water standards are used to evaluate both influent and effluent water quality of the system (see Table 3). It is understood that the influent concentration for Zn(II), Pb(II), Ni(II), and Fe(III) have already fulfilled class IIB water requirement. However, after the synthetic stormwater passed through biofiltration system, the concentration for these pollutants were reduced further. Table 22 shows the improvement of the water quality after passing through the biofiltration columns. Overall, all columns could remove TP up to 90% removal. Reduction of Zn(II), Pb(II), Ni(II), and Cu(II) were able to achieve more than 95% which is matching with the literature (Li and Davis, 2008; Read et al., 2008; Hatt et al., 2011; Reddy et al., 2014b; Wang et al., 2017b). Highest TN removal was achieved by CA columns with 38.01% followed by CF with 29.90%, GP with 20.05%, and BE with 16.67%. However, Mn(II) removal in CA was minimum with 50.43% removal compared to BE with 63.09%, GP with 97.39%, and CF with 97.72%. Poor Fe(III) removal was obtained for all columns with CF being the lowest with 42.18% and BE being the highest with 71.94%. However, since the inlet concentration of Fe(III) was already at class IIB based on Malaysia water standard, therefore any reduction of Fe(III) concentration was considered effective. In general, the utilization of biofiltration system with native Malaysian plants was considered successful since the effluent could meet the criteria for Malaysian standard for irrigation purpose (class IV).

Table 22: Summary of effluent water quality in seasonal columns study.

	Zn(II)	Pb(II)	Ni(II)	Fe(III)	Mn(II)	Cu(II)	TN	TP
Synthetic stormwater								
Inlet concentration (ppm)	0.250	0.140	0.030	0.860	0.230	0.150	4.32	1.12
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class V	Class IV	Class V	Class IV
Column CF								
Avg. removal (%)	98.20	96.79	96.67	42.18	97.72	96.33	29.90	88.82
Avg. outlet concentration (ppm)	0.005	0.005	0.001	0.497	0.005	0.006	3.03	0.13
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IIB
Column GP								
Avg. removal (%)	98.50	97.32	97.50	59.65	97.39	96.33	20.05	87.70
Avg. outlet concentration (ppm)	0.004	0.004	0.001	0.347	0.006	0.006	3.45	0.14
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IIB
Column CA								
Avg. removal (%)	97.90	97.32	97.50	69.59	50.43	96.33	38.01	89.71
Avg. outlet concentration (ppm)	0.005	0.004	0.001	0.262	0.114	0.006	2.68	0.12
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IIB	Class IV	Class IIB
Column BE								
Avg. removal (%)	98.63	95.64	89.52	71.94	63.09	97.67	16.67	86.20
Avg. outlet concentration (ppm)	0.003	0.006	0.003	0.241	0.085	0.003	3.60	0.15
Classification	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IIB	Class IV	Class IIB

*Operating pH: 6-7

CHAPTER 7
SURVIVABILITY AND FUNCTIONALITY OF TROPICAL BIOFILTRATION SYSTEM

7.1 Initial Concentration of Metals Ion in the Soil Media

For all biofiltration systems used in this study, sand batches originated from a local supplier were used. However, it is understood that the sand may naturally contain few pollutants before even being exposed to the synthetic stormwater. Therefore, a study was conducted on the natural sand material to understand its natural characteristics. An experimental setup consisting of 3 columns was prepared. Columns with diameter of 160 mm were filled with the layered media following the design described in section 4.3. Then, the columns were watered with tap water to flush the system. Samples were collected from the outlet to measure the concentration of heavy metals. The flushing was done 4 times and 2 samples (per column) were collected for each flushing round resulting in total of 8 samples for each column. The concentration of heavy metals resulted in this experiment are shown in Figure 23. As it can be seen, the Mn(II) content is naturally high in the soil media. It was evident as the concentration of Mn(II) in the first flushing session was 4.973 ppm (average value of 3 columns) while after fourth rounds of flushing it reduced to 0.427 ppm (91.41%, reduction). Moreover, a noticeable decreasing pattern was also observed for Fe(III) and Zn(II) where initial concentrations for Fe(II) and Zn(II) dropped from 1.282 ppm and 0.817 ppm to 0.098 ppm and 0.059 ppm, respectively. Throughout this study, the biofiltration columns were flushed for 3 times prior to the actual experiments in order to minimize the impact of natural soil heavy metals content on the pollutant removal efficiency. Therefore, high concentration of Mn(II) was still found in parts of the study (see section 5.5, 6.3.3, and 6.4.5).

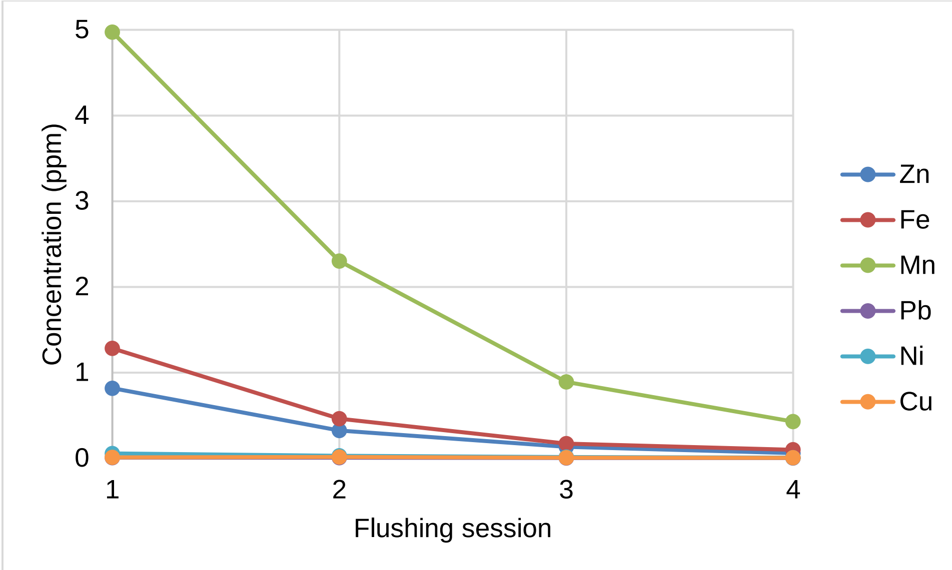


Figure 23: The changes on heavy metal concentrations during flushing process.

7.2 Effect of Submerged Zone Height on Plants Survivability and Treatment Performance

Submerged zone as one of the most important parts of a biofiltration system, plays a key role in survivability of the plants. In order to assess the impact of submerged zone water level on the plants survivability and also pollutants removal performance, a vegetated soil column study was conducted with varying submerged zone water levels. In the vegetated columns study in chapter 6, the submerged zone height of 250 mm was used which lies on the middle of transition layer of the system. In this study, three different levels of submerged zone were considered including 150, 250, and 350 mm above the outlet where the water levels lie in the drainage layer, transition layer, and filter media, respectively (see Figure 24). In this study, *Bambusoideae* was chosen as the plant due to its observed sensitivities to dry condition during the monitoring stage. Four replicates were prepared for each setup to assure the reliability of the findings. The purpose of this study was to explore the potential impact of such change on the survivability of the plants and pollutants removal efficiency of the system. In this experiment, infiltration rate and pollutants removal efficiency were measured 7 times for 35 days of experiment with different dry days gap. The dry days gap used in this study were 0, 1, 2, 3, 5, 7, and 10 days. The average value of both infiltration rate and pollutant removal efficiency throughout the experimental period were recorded.

Figure 24: Setup of submerged zone study with *Bambusoideae*

The results on the infiltration rate can be seen in Figure 25. It can be noticed that by increasing the submerged zone level, infiltration rate value is decreasing. This was obviously expected as infiltration rate is directly proportional to the water head. With 150 mm submerged zone height, the value of infiltration rate was ranged between 828 and 956 mm/hr. This figure was 530 - 782 mm/hr and 454 - 509 mm/hr for submerged zone heights of 250 mm and 350 mm, respectively.

The pollutant removal efficiencies of columns with different submerged zone heights are provided in Table 23. As it can be seen, the percentage removal for all pollutants are generally the best in columns with 350 mm submerged zone height except for Mn(II). This finding is consistent with literature where lower value of infiltration rate would promote larger residence time which in turn improves pollutant removal efficiency (FAWB, 2009). In another study of submerged zone by Blecken et al. (2009a) with four different height (0, 150, 450, 600 mm), it was concluded that 450 mm submerged zone perform the best in removing heavy metal ions Cu(II), Pb(II), and Zn(II). However, authors did not cover other pollutants as described in this study. The anomaly for Mn(II) in this study is related with the initial concentration of Mn(II) in the soil as discussed in section 7.1. On the other hand, columns with the lowest submerged zone height (150 mm) produced lowest pollutant removal percentage due to their higher infiltration rate. Considering both infiltration rate value and pollutant removal efficiency, this study confirms that the submerged zone height of 250 mm is perhaps a reliable value for being used in tropical biofiltration system; thus, it is recommended.

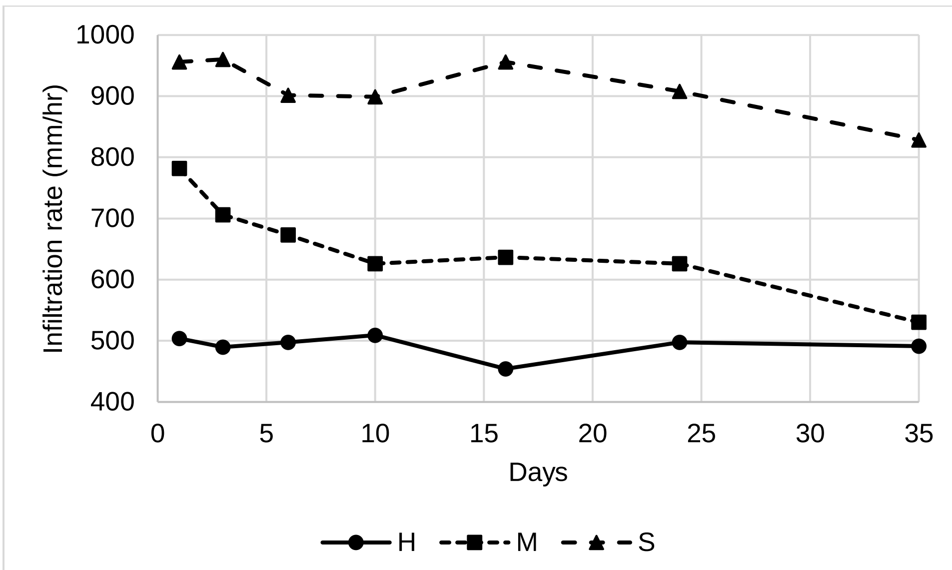


Figure 25: Infiltration rate value of different submerged zone height.

Table 23: Pollutant removal efficiency of columns with various submerged zone height.

Submerged zone height	Percentage removal (%)							
	Zn(II)	**Pb(II)**	**Ni(II)**	**Fe(III)**	**Mn(II)**	**Cu(II)**	**TP**	**TN**
350 mm	98.80	96.33	89.17	78.72	45.43	97.50	86.23	23.43
250 mm	98.63	95.64	88.89	72.35	57.79	97.44	86.20	23.14
150 mm	98.34	95.43	88.57	63.57	58.84	97.33	85.63	21.78

7.3 Long term efficiency

Maintenance and lifespan of biofiltration system has been well-studied in the past. Topics such as soil saturation by heavy metals, filter media clogging, and plant stresses are among the most important ones. In this study, the long-term study of the biofiltration system was conducted by summarizing the clogging potential, plant stresses, and reduction of pollutant removal efficiency during the experimental period. Clogging potential was observed by looking into decreasing pattern of infiltration rate value, while plant stresses was observed by looking into the survivability of the plants. Table 24 summarizes the lifespan study for each biofiltration columns. In general, infiltration rate value of non-vegetated columns was significantly lower than vegetated columns. In addition, non-vegetated columns were more prone to clogging with the few noticeable drops in infiltration rate value after 1 month of experiments, such as FA2%, MB2%, and FA5%. Although vegetated columns have higher infiltration rate, clogging potential was still observed, especially in plant PT, CA, and BE.

Plant stresses were observed in PT, HP, HS, CF, and GP. Plant PT could not survive after 5 months of experimental period due to the periodic watering with synthetic stormwater. Although the experiment on HP and HS were supposed to be conducted for the same 5 months, they were found to be extremely sensitive towards nutrients pollution. Since HP and HS were dried up after 2 months and 1 months, respectively, the sampling sessions were not continued. CF and GP showed minor stress such as falling leaves. However, this phenomenon was observed only during dry period simulation with longest dry days gap of 21 days. After the sampling sessions were concluded (last sampling was on 21 dry days gap), the columns were kept and watered on a weekly basis. It was found that both CF and GP can grow their leaves back once more frequent watering is introduced.

In terms of reduction in pollutant removal, as it can be seen in Table 24, reduction of Fe(III) removal was the most frequent problem compared to the other pollutants. In seasonal study of vegetated columns, Fe(III) removal was reduced for all columns. This was attributed to the potential cracks caused during the dry period which in turn resulted in less resident time. In addition, Fe was in the form of Fe(III) while other metals were in the form of M(II); therefore, the removal of Fe(III) was more unlikely as it has been explained in section 5.5. The reduction of nutrients removal was observed only in HP and HS columns. This is related to the fact that both plants were stressed out due to nutrients imbalance.

Considering the studies done and the fact that a tropical biofiltration system is exposed to a higher volume and frequency of stormwater when compared to other climate conditions, it is recommended to have a more frequent maintenance works for tropical biofilters to maintain high efficiency of the system. Such examples of maintenance works are scraping of topsoil to reduce pollutants accumulation, replanting, and manual watering during long drought period. It is hypothesized that the accumulation of the pollutants could start affecting the results of the study after approximately 3 – 5 years of constant watering with synthetic stormwater. Based on the results obtained in this study, a manual watering practice of once in 14 days could be adopted during a drought period. It is obvious that the estimation of the required maintenance cycles is depending on the typical pollutants concentration of the study region, total number of rainy days per year, as well as the adopted composition and depth of the filter media.

Table 24: Summary of lifespan observation during experimental period.

Columns	Duration of experiment	Reduction of infiltration rate	Plant stresses	Reduction of pollutant removal
Non-vegetated columns study				
No fine-grained materials	1 month	401 to 384 mm/hr (4% reduction)	N/A	-
Fly ash (FA) 2%	1 month	212 to 175 mm/hr (17% reduction)	N/A	-
Zeolite (Z) 2%	1 month	210 to 208 mm/hr (1% reduction)	N/A	Mn(II)
Hals – (MB) 2%	1 month	403 to 344 mm/hr (15% reduction)	N/A	Fe(III), Mn(II)
Hals – (UHP) 2%	1 month	297 to 287 mm/hr (3% reduction)	N/A	-

Table 24 continued…

Fly ash (FA) 5%	1 month	106 to 84 mm/hr (21% reduction)	N/A	-
Zeolite (Z) 5%	1 month	133 to 117 mm/hr (12% reduction)	N/A	-
Hals – (MB) 5%	1 month	272 to 249 mm/hr (8% reduction)	N/A	-
Hals – (UHP) 5%	1 month	165 to 158 mm/hr (4% reduction)	N/A	-
Vegetated columns study – non-seasonal				
***Pedilanthus tithymaloides* (PT)**	5 months	259 to 191 mm/hr (26% reduction)	Rapid falling of leaves and dried	-
***Heliconia psittacorum* (HP)**	2 months	361 to 330 mm/hr (9% reduction)	Nutrients imbalance	Fe(III), TN
***Hymenocallis speciosa* (HS)**	1 month	361 to 322 mm/hr (11% reduction)	Nutrients imbalance	Fe(III), TN, TP
Vegetated columns study – seasonal				
***Cordyline fruticosa* (CF)**	3 months	728 to 710 mm/hr (2% reduction)	Falling leaves during dry period	Fe(III)
***Graptophyllum pictum* (GP)**	3 months	520 to 530 mm/hr (2% increment)	Wilting and falling leaves during dry period	Fe(III)
***Cyperus alternifolius* (CA)**	3 months	661 to 466 mm/hr (30% reduction)	-	Fe(III)
***Bambusoideae* (BE)**	3 months	782 to 520 mm/hr (34% reduction)	-	Fe(III)

CHAPTER 8
CONCLUSION AND FUTURE WORK

8.1 Conclusion

The first objective of this study is to develop an appropriate soil media composition for tropical biofiltration system. A comprehensive study has been done on four fine materials named fly ash (FA), zeolite (Z), Hals – Matauri Bay (MB), and Hals – UltraHaloPure (UHP) to be used in biofiltration columns study with sand-based filter media. It is noted that both MB and UHP were proposed as novelty of this study. The findings on this study are summarized as follows:

- The usage of all four materials positively affect the heavy metal ions removal when compared to control columns except for Fe(III) in 5% UHP.
- Fe(III) was not removed well in columns with 5% UHP content due to the leaching of limonite mineral from the system and/or effect of pH where in 2% UHP, Fe is present as Fe(III) that is easier to be captured while the lower pH in 5% UHP makes Fe exist as soluble Fe(II) that slows percolation rate.
- The usage of 5% fine-grained materials was not preferred due to the noticeable reduction of infiltration rate value (34 – 75% reduction) in comparison with control columns.
- By considering both heavy metal ions removal efficiency and infiltration rate value, filter with 2% UHP was found to be the best composition followed by 2% MB and control columns.
- Good potential of using Hals in biofiltration systems was observed specifically in tropical regions.

The second objective of this study is to identify appropriate tropical plants for being used in tropical biofiltration system. In this study, ten plant species were grown and monitored in greenhouse before being selected to be implemented in the biofiltration columns study. Due to various responds from each plant, the study was classified into non-seasonal study and seasonal study of biofiltration columns. The highlights of the studies are summarized below:

- After monitoring plants stress and condition for 6 months, it was observed that 3 plant species were not able to survive, namely *Cymbopogon nardus* (CN), *Hibiscus rosa-sinensis* (HR), and *Iris pseudacorus* (IP); thus these 3 plant species were not used in biofiltration columns study.
- *Pedilanthus tithymaloides* (PT), *Heliconia psittacorum* (HP), and *Hymenocallis speciosa* (HS) were studied under non-seasonal tropical biofiltration study and were dried up after 150, 60 and 40 days respectively due to nutrients imbalance from synthetic stormwater.
- Infiltration rate value on PT, HP, and HS were found to be 191, 330, and 322 mm/hr respectively while control columns had infiltration rate of 23 mm/hr, thus proving the plant's root could improve the infiltration rate of the systems.
- Notable improvement on Total Nitrogen (TN) removal was observed on plant PT, HP, and HS at 29, 23, and 17% respectively compared with 7% removal in control columns, showing the plant's uptake helps in removing TN.
- Total Phosphorus (TP) removal was not significantly improved by the helps of the plants in non-seasonal vegetated columns study (3 – 7% improvement).
- *Cordyline fruticosa* (CF), *Graptophyllum pictum* (GP), *Cyperus alternifolius* (CA), and *Bambusoideae* (BE) could survive throughout the seasonal study with maximum of 21 dry days gap.
- CF had the highest value at 710 mm/hr due to the thick fibrous root system that allows pathway for water to infiltrate to the system, while the lowest infiltration rate was achieved by CA with 465 mm/hr due to the massive root growth that may cause soil compaction.
- CA had the highest removal of nutrients (TN at 38% and TP at 90%) in comparison with other columns due to the massive root growth supported by the fact that nutrients uptake is mostly occurring on plant's root.
- BE had the lowest TN removal (17%) compared with other columns due to their grass-family plant classification that needs lower amount of nutrients to live.

- The outlet water quality of all vegetated columns were able to achieve class IV water for irrigation purpose based on Malaysia discharge water standard.
- CA is promising to be used in tropical biofiltration system due to the survivability under high pollutant load on both wet and dry condition, and the high pollutants removal efficiency especially TN.

The third and last objective is to find the general needs for survivability of the selected plants which are operating in tropical biofiltration system, as well as the functionality of tropical biofiltration system. Three assessments were completed in this section including initial metal ions concentration on the sand-based media, effect of submerged zone height on the system performance, and long-term efficiency study. The findings on these studies are summarized below:

- The sand-based media that was used in the columns study contained Mn(II) concentration of 4.973 ppm. By flushing the system with tap water four times, the concentration of Mn(II) was dropped to 0.427 ppm. Therefore, at least three rounds of tap water flushing for each column were recommended prior to the experiments to remove majority of the Mn(II) concentration.
- Higher submerged zone levels decreased the infiltration rate due to the reduction of water head. However, pollutant removal efficiency was found to be better in higher level of submerged zone. By considering both infiltration rate and pollutant removal factors, 250 mm of submerged zone level is recommended to be used in tropical biofiltration system.

8.2 Future Work

Several options to expand and refine this current thesis work are listed below:

1. Although adding fine materials such as MB or UHP would reduce the infiltration rate, it has not been known how it may perform when it is implemented in vegetated biofiltration study. Based on the results obtained in this thesis, the usage of fine

materials may be able to improve the removal of Fe(III) that was not efficiently removed in vegetated biofiltration study.

2. In this study, sampling points were located at the middle of drainage layer of the soil media. To analyze and understand the removal process better, it is possible to increase the number of sampling points at different layer of the media (transition and filter). Although there was study about this topic, there was not any on tropical biofiltration system. Since the infiltration rate in tropical biofilter is generally higher, it is expected that it may affect the pollutant removal process in the system.
3. This study was focusing on experimental work with PVC columns. An expansion of this project can be proposed by moving the system into field study. In the field scale biofiltration system, there are few factors that need to be included as design specification, such as combination of plants and slope for incoming water. Since ultimately this study is projected towards field scale of tropical biofiltration system, it is recommended to expand the project.

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APPENDIX A
SAMPLE CALCULATION OF SYNTHETIC STORMWATER PREPARATION

Example: preparation of 0.14 ppm of Pb(II) from $Pb(NO_3)_2$.

Molecular weight of $Pb(NO_3)_2$ = 331.21 g/mol

Molecular weight of Pb = 207.20 g/mol

% of Pb in $Pb(NO_3)_2$ = 207.20 / 331.21 x 100%

= 62.56%

Target concentration = 0.14 mg/L

Assumption : preparation of 300 L synthetic stormwater

Mass of Pb in synthetic stormwater = 0.14 x 300

= 42 mg

Mass of $Pb(NO_3)_2$ needed = 100 / 62.56 x 42

= 67.14 mg

Similar calculation was done for all chemicals involved.

APPENDIX B

DETAILED CALCULATION OF STORMWATER DOSAGE

Assumption:

Catchment: Parking with paved surface (*Figure A-1*)

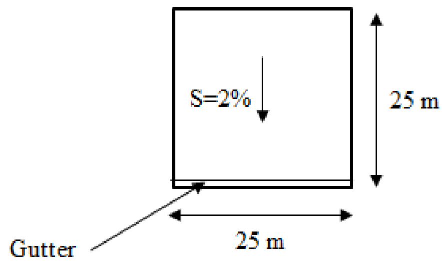

Figure A-1. Schematic Shape of the Hypothesized Catchment and its Drain

Step 1: Design Rainfall

Length of overland flow = 25 m

Refer to MSMA-Chart 14.1: t_0 = Overland travel time = 4 mins

Refer to MSMA-Section 14.4.2: V=1 m/s → t_g = gutter travel time = 25 / 1 = 25 s = 0.4 mins

Time of concentration: $t_c = t_0 + t_g$ = 4+0.4 = 4.4 mins ≈ 5 mins

To find rainfall intensity for a 5 minutes 3-months ARI event, the following steps are needed:

Step 1-1: Finding total rainfall of an event with duration of 5min for 2-years ARI event (${}^{2}P_{5\min}$)

$${}^{2}P_{5\min} = {}^{2}P_{30\min} - F_D({}^{2}P_{60\min} - {}^{2}P_{30\min}) \quad \text{(Eq.A1)}$$

Where ${}^{2}P_{30\min}$ and ${}^{2}P_{60\min}$ are the rainfall value of events with 30 and 60 minutes duration and 2-years ARI; F_D is the adjustment factor. For finding ${}^{2}P_{30\min}$ and ${}^{2}P_{60\min}$ the regression formulas of IDF relationship (Intensity-Duration-Frequency) for Ipoh are used. The IDF formula for 2-years ARI events in Ipoh can be given by (MSMA-Table 13-A1):

$$Ln({}^{2}I_{t}) = 5.2244 + 0.3853Ln(t) - 0.1970[Ln(t)]^{2} + 0.01[Ln(t)]^{3} \quad \text{(Eq.A2)}$$

Where t is the rainfall duration and ${}^{2}I_{t}$ is the rainfall intensity for 2-years ARI. Using Eq.A2 and considering t as 30min and 60min:

${}^{2}I_{30} = 104.5$ mm/hr → ${}^{2}P_{30\min} = 104.5 \times (30/60) = 52.3mm$

${}^{2}I_{60} = 65.8$ mm/hr → ${}^{2}P_{60\min} = 65.8 \times (60/60) = 65.8mm$

Referring to MSMA-Table 13.3 and Figure 13.3: $F_D = 2.08$

Then, we need to put all the calculated values in Eq.A1 to find ${}^{2}P_{5\min}$:

$$ {}^{2}P_{5\min} = 52.3 - 2.08(65.8 - 52.3) = 24.2 \ mm$$

Step 1-2: Finding the rainfall intensity of an event with the duration of 5min for 2-years ARI event (${}^{2}I_{5\min}$)

$$ {}^{2}I_{5\min} = {}^{2}P_{5\min} / (5/60) = 24.2/(5/60) = 290.2 \ mm/hr$$

Step 1-3: Finding the rainfall intensity of an event with the duration of 5min for 3-months ARI event (${}^{3-months}I_{5\min}$)

Referring to MSMA-Section 13.2.8 we get:

$${}^{3-months}I_{5\min} = 0.5 \times {}^{2}I_{5\min} \quad \text{(Eq.A3)}$$

Replacing the calculated value for ${}^{2}I_{5\min}$ in Eq.A3 we have:

$${}^{3-months}I_{5\min} = 0.5 \times 290.2 = 145.1 \ mm/hr$$

Step 2: Design Runoff

By referring to MSMA-Chart 14.3 the runoff coefficient for the given rainfall intensity and assumed surface will be C = 0.9. Then the rational formula can be applied to calculate the resulted runoff of the design rainfall:

$$Q = 0.00278CIA \qquad \text{(Eq.A4)}$$

Where Q is the peak runoff (m^3/s), C is runoff coefficient, I is rainfall intensity (mm/hr) and A is the catchment area (ha).

So,

$$Q = 0.00278 \times 0.9 \times 145.1 \times 0.0625 = 0.023 \ m^3/s$$

Step 3: Treatable Runoff Volume (V_W)

Using the ideal triangular shape hydrograph (recommended by MSMA), the treatable runoff volume can be calculated (*Figure A-2*)

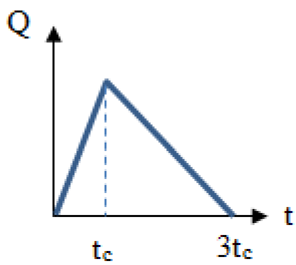

Figure A-2. Schematic Shape of Ideal Triangular Hydrograph Recommended by MSMA for Calculating Runoff Volume

Therefore, by having t_c = 5min we have

$$V_w = \frac{3(5 \times 60) \times 0.023}{2} = 10.215 \ m^3$$

Step 4: Porosity in the system

$V_T = V_s + V_v$ (Eq.A5)

Where V_T is the total volume of the column to the topsoil level, V_s is the volume of the soil in the column, and V_v is the volume of the void in the column. Following the column structure, V_T can be calculated while V_v was measured and found to be 7.25 liters.

$V_T = \Pi*0.2^2/4*0.835 = 0.02623\ m^3 = 26.23$ liters

$V_s = V_T – V_v = 26.23 – 7.25 = 18.98$ liters

Void ratio, e is then calculated by the ratio between V_v and V_s, thus

$e = V_v/V_s = 7.25/18.98 = 0.382$

After that, porosity n can be calculated

$n = e/(1+e) = 0.382/(1+0.382) = 0.276$

Step 5: Required Basin Area

The volume of water that must be stored in basin can be obtained by (MSMA-Eq.21.8):

$V = V_w + PA_b – f_d\ T\ A_b$ (Eq.A6)

Where *V* is the volume of the stored water, V_w is the volume of treatable water, *P* is the rainfall amount, A_b is the basin area, f_d design infiltration rate, and *T* is the effective filling time (recommended to be less than 2 hr). Putting the available values and calculated the other required ones in Eq. A5 we can find A_b.

$V = Freeboard(FB) * A_b + n*H*A_b$

Where it is FB=0.165 in column and is assumed to be the same in the basin. H is the unsaturated soil height due to the presence of submerged zone, which is 0.45 m.

P is the total rain happens during the same amount of time that V_w was calculated based on that:

$P = 3 * t_c = 3\ (24.2) = 72.6\ mm = 0.0726\ m$

So,

$$0.165A_b + 0.276 \times 0.45 \times A_b = 10.215 + 0.0726A_b - 0.1 \times 2 \times A_b$$

$A_b = 24.55\ m^2$

Step 5: Required Dosage

The required dosage is related to the cross section area of the column. In this study, 2 sizes columns were used with diameter 160 mm (chapter 5) and 200 mm (chapter 6). If we calculate the ratio of areas of the basin over column cross section we get the dosage volume for each rainfall event for every column.

Case 1: diameter 160 mm

$R=A_b / A_{column} = 24.55 / (\Pi*0.16^2/4) = 1221.02$

$V_{column} = V_b / R = 10215$ (liter) / 1221.02 = 8.36 liters

Case 2: diameter 200 mm

$R=A_b / A_{column} = 24.55 / (\Pi*0.2^2/4) = 781.4$

$V_{column} = V_b / R = 10215$ (liter) / 781.4 = 13.07 liters

Based on MSMA – Section 13.4.7, 93% of total rainfall occurs in storms is equal to or smaller than the 3-months ARI rainfall in Ipoh. Considering 168 rainy day in Ipoh based on historical data we can conclude that 0.93 * 168 = 156 days in each year could face such event. Therefore:

365 / 156 = 2.3 days

This means for 200mm diameter column, a dosage of 13.07 liters is required in each 2.3 days which is approximately 6 liters per day.