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Evaluation of the different filter media in vertical flow stormwater wetland

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ABSTRACT

The performance of four different types of filter media, namely woodchip, pot gravel, synthetic fiber, and volcanic stone employed as the main media in a set of column vertical flow stormwater wetlands were evaluated in this study. The evaluation parameters were treatment performance, adsorption capacity, porosity, filtration type, plant growth, substance release, cost, and construction. For pollutant removal, all the media showed efficient reduction of total suspended solids (more than 80%). Similarly, all were efficient in organics removal except for woodchip but it had the highest total nitrogen removal efficiency for 40%. total phosphorous removal was high in synthetic fiber and pot gravel (75 and 65%, respectively) but it was poor in volcanic stone. Pot gravel showed the highest adsorption capacity followed by volcanic stone but their disposal cost may be a burden. Although synthetic fiber has the highest porosity, it was thought to be capable of only surface filtration due to its small pore size while the others were expected to be capable of in-depth filtration. In terms of cost, woodchip was the cheapest followed by pot gravel and volcanic stone, while synthetic fiber was the most expensive. Finally, in terms of construction, all the media are advisable for use except for volcanic stone due to its high loading that can increase construction cost and due to difficult management during construction as well as replacement.

Keywords: Media; Stormwater; Vertical flow wetland

1. Introduction

Vertical flow (VF) wetlands, as a type of constructed wetlands, are used worldwide for removing pollutants from wastewater or stormwater runoff due to their mechanical simplicity, low operational and maintenance requirements in comparison to conventional water treatment technologies. The most important consideration in the design of this type of wetland is the filter media, which is closely related to the pollutant removal, wetland running time, and construction cost.

A great number of previous studies have focused mainly on the treatment performance of wetland

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media. Different media such as sand, zeolite, gravel, organic materials, and artificial slag have been used in VF wetlands and displayed their priority on the removal of certain kinds of pollutants. For example, gravel is most commonly used for the purpose of treatment. A study by Białowiec et al. [1] showed that gravel was conducive to total nitrogen removal. Others have also employed the use of organic materials as the media. Robertson [2] found out that wood particle media particularly sawdust and woodchips have shown an ability to deliver consistent rates that give longer term (5–15 years) nitrate removal. On the other hand, Korkusuz et al. [3] found that the treatment performances of the slag-filled wetland were better than that of the gravel-filled wetland in terms of removal of phosphorus and production of nitrate. However, slag contains heavy metals that may lead to secondary pollution. Oppositely, zeolite was found to effectively remove heavy metals such as arsenic and iron in acid mine drainage with 92 and 86% efficiencies, respectively [4].

Running time of the wetland is related to the porosity and the grain size distribution of the media. Usually, higher porosity implies a larger potential for solid retention and a longer operation time due to delaying clogging. On the other hand, the grain size distribution influences the pore size distribution, active pore volume, and the clogging process in the wetland. Small particle size indicates a large specific surface area which is available for biofilm establishment and surface chemistry, but it is also highly prone to clogging [5,6]. Oppositely, large-size media can prevent or delay clogging [7,8].

Another factor to consider is the cost-effectiveness of the media. Usually, it is the most expensive component of the wetland and a proper filter media should not be considered only for the efficient removal of pollutants but also in terms of cost regarding construction and maintenance. Therefore, locally available resources have always been selected because they are economically viable and acceptable for use in the fields [9].

Moreover, media also affects wetland plants that have a potential for transporting oxygen to the deeper part of the filter. In this zone, oxygen concentrations were usually low but sufficient for aerobic biomass activity. Many studies have focused on the nutrient uptake of plants and their contribution to the improvement of treatment performance. However, few studies have investigated their adaptation to the media in VF wetlands [10].

Selecting the proper media is critical not only for pollutant removal but also for operation, maintenance and cost considerations. Therefore, in this study, four different media were evaluated based on the data gathered from a laboratory-scale VF column wetland treating stormwater runoff. Criteria for evaluation were treatment performance, adsorption capacity, porosity, filtration type, plant growth, substance release, cost, and construction.

2. Materials and methods

2.1. VF stormwater wetland design

A downward VF column wetland was used in this study. The column was made of dark opaque acryl, with a diameter of 0.1 m and a total length of 1 m which is identical to the full-scale system planned in the future. Saturated zone and unsaturated zone in the column wetland were both taken into consideration. In addition, *Acorus Calamus* was planted with roughly the same biomass in each column wetland.

Woodchip, pot gravel, synthetic fiber, and volcanic stone were selected as the main filter media. The arrangement of filled media in each column from top to bottom were small pot gravel (5 cm), big stone (5 cm), main media (55 cm), medium stone (10 cm), and big stone (10 cm) (Fig. 1).

2.2. Operation

The stormwater collected from an asphalt-paved road bridge was used as the inflow. 2.1 L of stormwater was fed to each column in 1.5 min. The instant approach velocity was estimated to be approximately 243 m/day. In order to know the effect of multiple passes on pollutant removal, the outflow was recycled after 24 h of retention and the recycle frequencies were 1, 3, and 7, times, respectively, in each group. After the end of the recycling process, the outflow was collected and tested in the laboratory.

All the 12 column wetlands were put outdoors and were operated for four months from 15 July to 21 November 2011.

2.3. Parameters

Water samples were tested for temperature, pH, conductivity, turbidity, total suspended solids (TSS), total COD (TCOD) and soluble COD (SCOD), total nitrogen (TN), NH_3–N, NO_3–N, total phosphorous (TP), and dissolved TP (DTP). Temperature, pH, and conductivity were measured with YSI 556 portable instrument while turbidity was measured with HACH 2100 N Turbidimeter. The others were determined according to the Standard Methods for the Examination of Water and Wastewater [11].

The specific surface area and pore volume were measured according to the Brunauer–Emmett–Teller

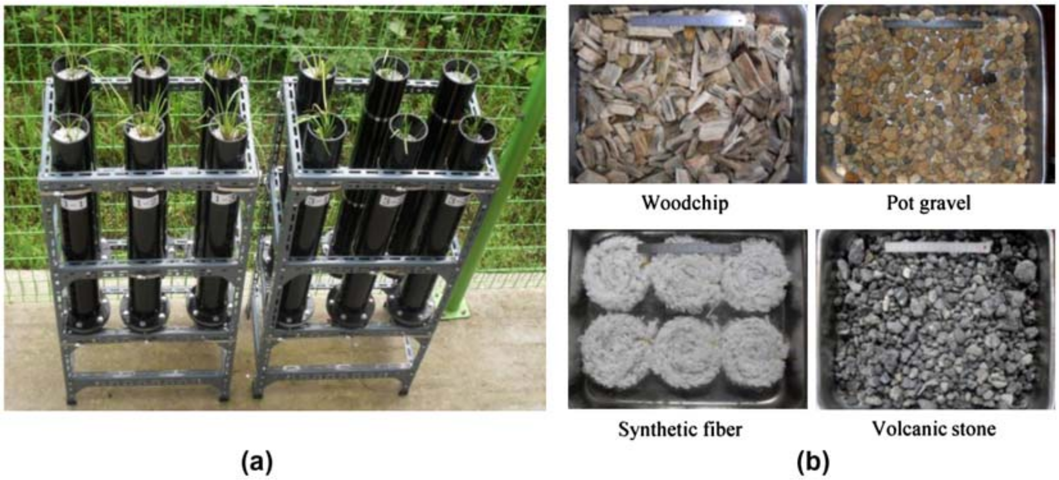

Fig. 1. Photos of the VF stormwater wetlands and the media used in this study.

(BET) method using Belsorp II Volumetric Adsorption Analyzer. The analysis of type of filtration was based on the operational data, porosity, and the grain size distribution. Root length and biomass were the main components of consideration in the evaluation of plant growth. Media cost was determined with reference to the market price in Korea and was changed into US dollars.

3. Results and discussion

3.1. Treatment performance

The pollutant removal performance of these column wetlands was stabilized after an acclimation phase of about 30 days. The removal efficiencies during the stable period are shown in Fig. 2.

Firstly, for TSS removal (see Fig. 2(a)), high efficiency was observed regardless of the media type with the highest value of 95% in the synthetic fiber. The reduction of organic matter in all the media was also efficient except for woodchip, due to its nature as an organic material.

As for nitrogen removal (see Fig. 2(c)–(e)), which relies on the microbial nitrification followed by denitrification in constructed wetlands [12], woodchip showed a significant advantage with a average removal efficiency of 40% compared to the other three media ($p < 0.001$). Related to this, efficient ammonia transformation occurred in all the media but efficient denitrification only happened in woodchip wetland. This is because denitrification was enhanced by the abundant carbon source in this medium which provides energy for denitrifying microorganisms.

Finally, for phosphorus removal (see Fig. 2(f)), synthetic fiber displayed the highest efficiency for 75%, which is related to the highest removal on TSS since phosphorus is considered to be adsorbed to solids surface [13,14]. In addition, pot gravel also showed efficient TP removal, followed by woodchip. In contrast, the removal of phosphorus in volcanic stone was poor for about 20%.

3.2. Adsorption capacity

For water treatment, some adsorbents having high adsorption capacity, such as activated carbon and zeolite, are pursued because high adsorption capacity can enhance efficiency of pollutant removal by adsorbing more pollutants. In general, the specific surface area of ordinary activated carbons is 1,000–1,500 m^2/g [15]. Additionally, zeolite is another kind of key high-surface area material in adsorption technology [16].

The adsorption/desorption isotherms of these four types of media were measured using the gas adsorption method (BET method) and are shown in Fig. 3. The adsorption capacities are listed in Table 1.

Firstly, according to the standard adsorption isotherms [17], different kinds of pore structure of each type of medium can be indicated. Fig. 3(a), a standard isotherm III indicates a structure of macropore. Fig. 3 (b) and (d) show a standard isotherm IV, which means that volcanic stone and pot gravel have a similar porous structure called mesopore. Fig. 3(c) indicates that synthetic fiber shows a negative result which is impossible. In fact, this means that nitrogen gas leached out from the synthetic fiber during the BET measurement, which resulted in the negative values as shown in Table 1.

In addition, all the four types of media showed different adsorption capacities. Distinctively, synthetic fiber was not successfully measured using the BET

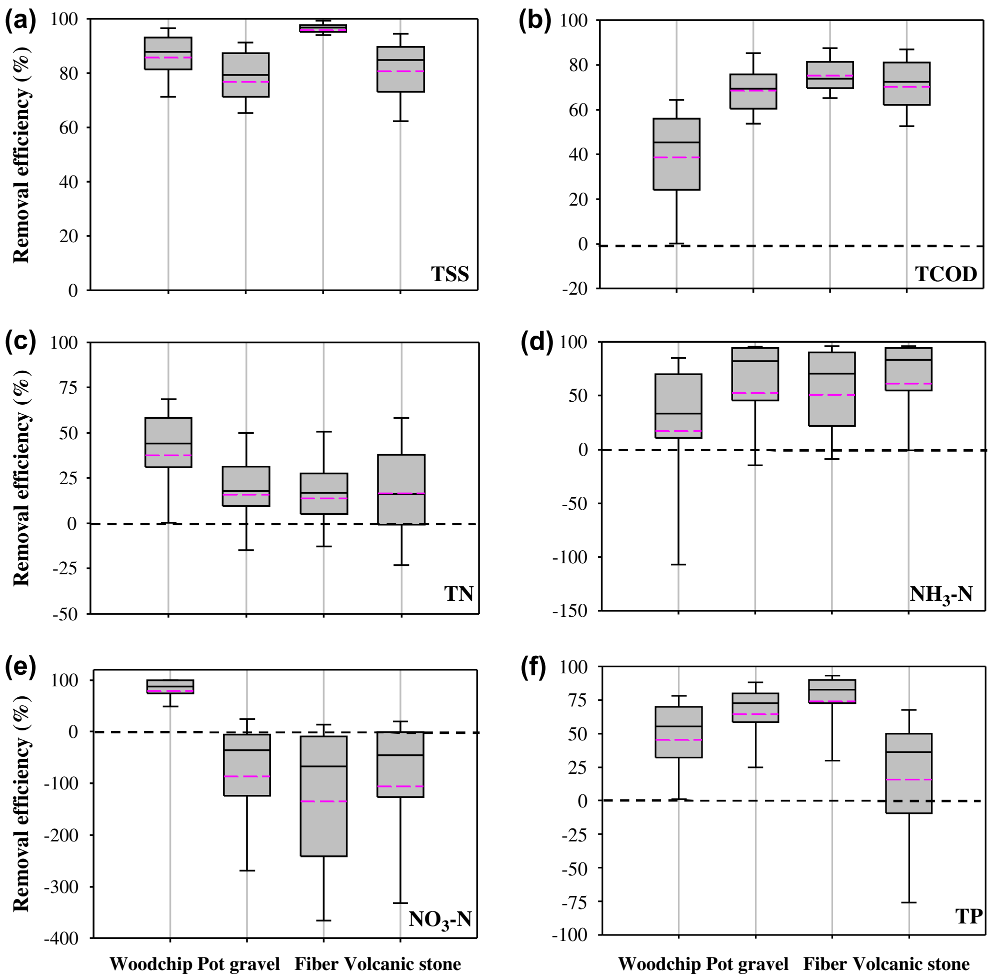

Fig. 2. Pollutants removal efficiency among different media.

method as discussed above. However, the producer provided a 1.5 m^2/m adsorption capacity of synthetic fiber, from which the specific surface area of synthetic fiber was calculated. Therefore, as shown in Table 1, pot gravel showed the highest total pore volume and specific surface area meaning that it had the highest absorption capacity among the four media, followed by volcanic stone, woodchip, and lastly synthetic fiber.

It is worth mentioning that, compared with activated carbon and zeolites which have high adsorption capacities as mentioned before, the adsorption capacity of the media used in the study is negligibly low.

Generally, a better adsorption capacity can give a better removal efficiency of pollutants. However, according to experiences in stormwater treatment with a filter-type best management practice, the disposal cost of some medium with a high adsorption capacity has been a burden when its adsorption capacity is exhausted later.

Due to the specific properties of these four media, the disposal of woodchip was relatively easy, since it can be disposed by burning or composting. In contrast, pot gravel and volcanic stone were more difficult to dispose, since the pollutants adsorbed inside were not easy to clean out. For synthetic fiber, it was also difficult to gather the particles adsorbed inside. Combining all the results, suitability order of media can be concluded as follows: woodchip, pot gravel, volcanic stone, and synthetic fiber.

3.3. Porosity

The porosity of the filter media depends on how well the grains fit together as well as the type and size of the media. As for the shape, generally, as the grain shape becomes less spherical, the porosity of a given volume increases [18].

The porosity of each type of medium is shown in Table 2. Firstly, the woodchip, which was cut into flat cuboids with the range in length from 2.6 to 11.5 cm, had a porosity of 66% which was the second highest among the four media.

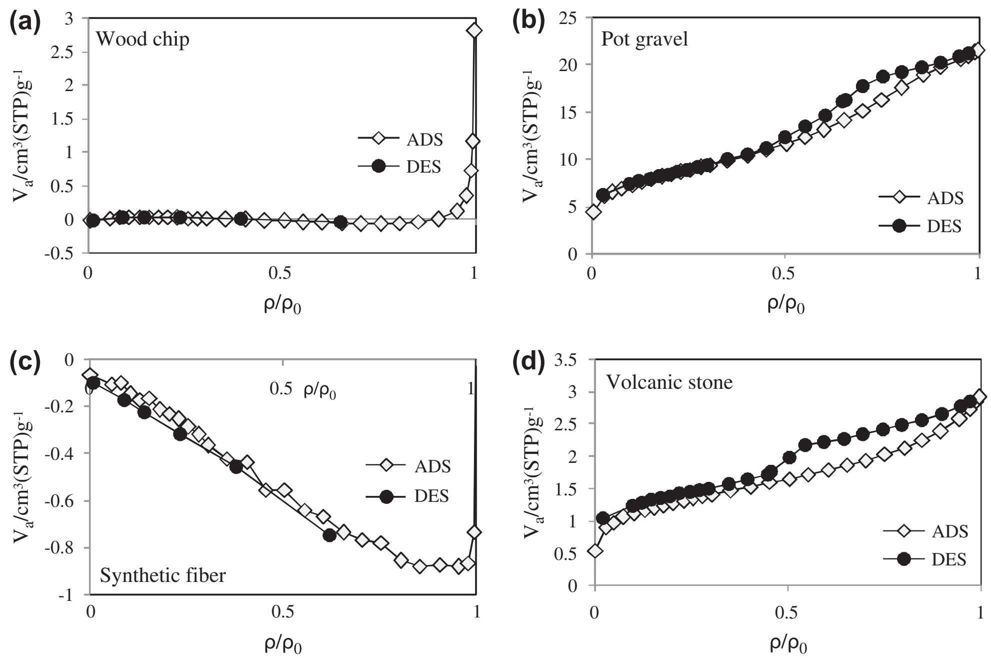

Fig. 3. Adsorption/desorption isotherms of four types of media.

Table 1
Adsorption capacity of different types of media

Media	Total pore volume ($p/p^{\circ}=0.990$) ($cm^3\,g^{-1}$)	Average pore diameter (nm)	As, BET ($m^2\,g^{-1}$)
Woodchip	0.0014221	60.327	0.094294
Pot gravel	0.032898	4.4539	29.546
Synthetic fiber	−0.0011932*	7.1572*	−0.66685*
	–	–	0.046612**
Volcanic stone	0.0044159	3.8749	4.5585

*Test result, **calculated result.

Table 2
Characteristics of filter media

Media	d_{10} (cm)	d_{50} (cm)	d_{60} (cm)	U^*	Porosity (%)
Woodchip	1.1	2.0	2.1	1.9	66
Pot gravel	1.0	1.2	1.3	1.3	51
Synthetic fiber	–	–	–	≈1.0	89
Volcanic stone	0.7	0.9	1	1.4	53

*Uniformity coefficient.

Pot gravel and volcanic stone showed approximate porosity of 53 and 51%, respectively, due to their similar shape and particle size distribution. Finally, synthetic fiber having a fluffy appearance and a very different shape from all the other media, displayed the highest porosity of 89%, indicating the highest potential to accommodate more solids and subsequently having the potential of the longest running.

To compare the grain size distributions of these media with the same standard, the grain size was replaced by the diameter of an equivalent volume of sphere. The following equation was used for the calculation of sphericity (ψ) [18]:

$$\psi = \frac{(\text{surface area of a sphere})/V_{\text{Sphere}}}{(\text{surface area of a particle})/V_{\text{Particle}}} \tag{1}$$

where volume of the sphere (V_{Sphere}) is set to equal to the volume of the media grain (V_{Particle}).

For woodchip, the value of ψ was approximately 0.47. For pot gravel and volcanic stone, the diameter (d) of the equivalent volume sphere is directly defined as follows:

$$d = \frac{L + W + H}{3} \tag{2}$$

where L is the length of the grain (cm), W is the width of the grain (cm), and H is the height of the grain (cm).

On the other hand, synthetic fiber is a uniform media. Thus, the uniformity coefficient was regarded as 1.

Based on the definitions above, the grain size distributions of the media are shown in Table 2. According to the grain distribution, woodchip has a relatively larger grain size and uniformity coefficient. Pot gravel and volcanic stone had a similar uniformity, but the latter had a smaller grain size.

3.4. Type of filtration

The success of VF type of wetland depends on how long it can be operated without clogging. The accumulation of suspended solids in the pore is considered to be the major factor related to this phenomenon.

Clogging preferentially develops in the upper layer of the medium. The accumulation of solids in the subsurface or on the surface of media reduces hydraulic conductivity in the former case and slows down infiltration to the subsurface in the latter case.

Usually, the smaller the grain size of the filter media, the higher the specific surface area available for biofilm establishment which is beneficial to treatment performance. However, this can also contribute to clogging and increase the likelihood of straining due to the narrower pore size. Therefore, fine media are prone to rapid clogging by pore blockage.

According to Table 2, smaller d_{10} and larger U implies smaller pore size which indicates that solids are more easily retained in the upper layer and shorten the effective pore volume. Oppositely, larger d_{10} and smaller U means larger pore size which is beneficial for the distribution of the solid particles throughout the whole layer of media, thus extending the running time of wetland.

In this context, synthetic fiber, having the smallest pore size, was prone to surface filtration and clogging, although it had the highest porosity among the media. In fact, filtration rate in synthetic fiber was always slower than the other three media and thus ponding was observed. For the other media, they had a relatively large pore size and tended to show in-depth filtration. Thus, the order of duration time without clogging was woodchip followed by pot gravel, and then volcanic stone followed by synthetic fiber.

3.5. Plant growth

Wetland plants play an important role in terms of nutrient uptake and oxygen transfer for aerobic microorganism in constructed wetlands. Also, a wetland plant that has a flourishing and long root system can enlarge the effective void volume of constructed wetlands for decontamination and be favorable for the microorganisms, especially for aerobic bacteria to expand their distribution into the depth of the wetland [19].

Dong et al. [20] studied the diurnal fluctuations in root oxygen release rate and dissolved oxygen budget in wetland mesocosm. He reported that the root oxygen release rate ranged from 20.3 to 58.3 $g\,O_2/m^2\,d$ with average value of 38.4 $g\,O_2/m^2\,d$. It was shown that 35 and 9% of the oxygen released by roots were used in the degradation of organic matters and nitrogen nitrification, respectively, while 56% was used for roots. Degradation, nitrogen nitrification and many other processes which relied on oxygen in the vertical wetland were enhanced by 44% of oxygen release from roots.

On the other hand, plant root can enlarge media porosity and produce a larger number of small pores. The potential running time of VF wetland is associated with pore volume while filtration rate is related with pore size. However, long and hairy root can shorten the VF wetland operation time due to clogging.

After about a culture period of four months, the lengths and the biomass of the plants were measured, and the results are provided in Table 3.

The woodchip group showed the longest roots, the densest root hair and also the largest biomass, which indicates that plants are able to easily root in this medium. On the contrary, the synthetic fiber group showed the least biomass, which indicates difficulty in its growth. In addition, the pot gravel and the

Table 3
Information on plant growth

Media	Initial plant length (cm)	Plant length (cm)	Root length (cm)	Root biomass (g/m^2)	Total biomass (g/m^2)
Woodchip	16.0 ± 1.0*	48.5 ± 17.1	33.0 ± 13.1	174.6 ± 119.6	276.1 ± 164.2
Pot gravel	18.0 ± 1.0	39.7 ± 6.8	23.8 ± 5.0	142.6 ± 29.0	229.9 ± 45.5
Synthetic fiber	16.3 ± 1.5	40.0 ± 7.9	21.8 ± 3.4	92.0 ± 15.1	186.8 ± 38.3
Volcanic stone	18.7 ± 0.6	42.0 ± 2.0	26.0 ± 5.3	127.5 ± 86.6	213.8 ± 142.4

*Average ± STDEV.

volcanic stone groups showed similar growths with intermediate values.

The growth of a plant is usually affected by soil, water content, soil fertility, and especially soil texture which is related to the holding capacity of water and fertility. Also, the content of organic matters which contains abundant essential nutrients for plant growth is usually regarded as an important attribute of soil fertility. As for woodchip, higher water-holding capacity and sufficient nutrient supply from organic matter provided enough energy for plants to extend its root. However, for pot gravel and volcanic stone, plant growth was restricted by the poor water-holding capacity and the less nutrient content. Finally, synthetic fiber, as a type of artificial material, provided poor growing conditions due to the poor water-holding capacity and the lack of nutrient and minerals. The denser structure and smaller pore size of synthetic fiber were also unfavorable factors for rooting.

3.6. Release

Due to the natural properties, some substances were leached out during operation. As shown in Fig. 4(a), soluble COD concentrations of the outflow in the woodchip group were obviously higher than that of the inflow. Meanwhile, the concentration of soluble COD increased with the increase of antecedent dry days (ADDs). As discussed in the previous section, the removal efficiency of total COD in the woodchip wetland was poor, implying that organic matter was released from the woodchip during operation. Woodchip was dissolved into the fed stormwater via microbial fermentation, since it mainly consisted of cellulose organic matters.

Similarly, the release of phosphorous was also found in the volcanic stone group (see Fig. 4(b)). The poor reduction of TP and the distinctly negative removal efficiency of dissolved TP support the fact that phosphorus was leached out from volcanic stone during treatment.

Also, it was observed that there were higher concentrations of NH_3–N in the outflow of wetlands with synthetic fiber during the acclimation phase (Fig. 4(c)). This is attributed to the dissolution of ammonia from the fiber (Nylon and Amine Synthetics) which contains basic nitrogen atoms. However, ammonia release was gradually decreased after the acclimation.

3.7. Cost

For future study, a full-scale VF stormwater wetland which has the same configuration with the laboratory-scale wetland in steel-reinforced concrete box structure is planned to be built. Its length and width are 10 and 5 m, respectively. The depth of the main media inside is also 55 cm, and the saturated and unsaturated zones are equally divided.

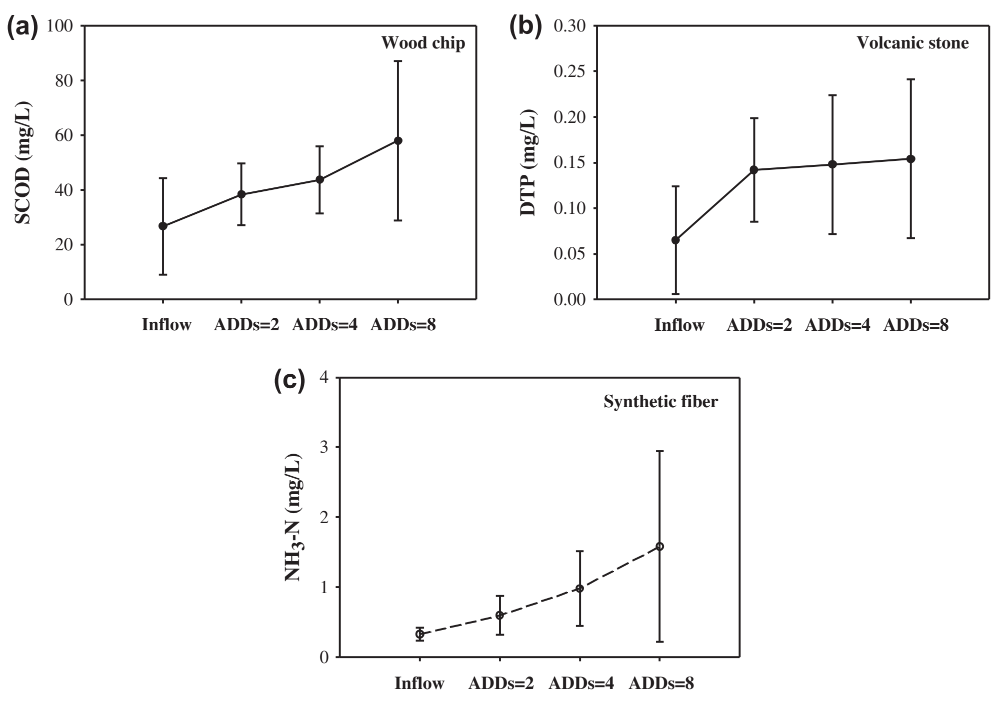

Fig. 4. Release of organic matters and nutrients from the media.

Table 4
Purchase cost of the four media

Media	Unit price	Amount	Cost ($\$/m^3$)
Woodchip	0.057 $\$/m^3$	27.5 m^3	57
Pot gravel	0.33 $/kg	11,000 kg	132
Synthetic fiber	3.09 $/m	125,125 m	14,059
Volcanic stone	0.31 $/kg	23,100 kg	260

Woodchip, pot gravel, synthetic fiber, and volcanic stone are presumed to be used in the full-scale wetlands. The costs for purchasing these media were calculated and compared as shown in Table 4.

According to this table, as a kind of natural and renewable material, woodchip showed the lowest cost of 57 $\$/m^3$. Pot gravel and volcanic stone, which are abundant in nature, displayed the costs of 132 and 260 $\$/m^3$, respectively. Finally, the artificial medium of synthetic fiber was the most expensive among all the media, costing 14,059 $\$/m^3$.

Table 5
Pressure from the main media layer

Media	Density* (kg/m^3)	Media weight (kg)	Water weight (kg)	Total weight (kg)	Load (kg/m^2)
Woodchip	260	7,150	9,075	16,225	325
Pot gravel	400	11,000	7,013	18,013	360
Synthetic fiber	120	3,300	12,238	15,538	311
Volcanic stone	840	23,100	7,288	30,388	608

*Packing density.

3.8. Construction

Based on the planned full-scale wetland in the future, design criteria such as loading, operation and maintenance as well as replacement considerations were assessed. The structure is an open rectangular steel-reinforced concrete box where the media will be placed. As mentioned in the previous section, this wetland is $10\,m \times 5\,m \times 1\,m$ in dimension and will be embedded in soil which will require foundation works. The loading at the bottom or slab will be the weight of the media and the water occupied by its pores. According to the packing density measured and the dimensions of the wetland, the total weight and load exerted by the media layer were estimated and summarized in Table 5. Among all the media, volcanic stone was the heaviest which resulted to a bottom load of 608 kg/m^2. Synthetic fiber was the lightest with only 3,300 kg in weight but due to its high porosity, the weight of the pore water was heavy and the resulting load was similar to those exerted by woodchip and pot gravel. The media also exert lateral pressure on the sidewall of the structure, and this pressure was assumed to be directly proportional to the vertical load (Fig. 5).

In regard to handling and construction, volcanic stone is not recommended because heavier media requires difficult handling measures as well as a more stable structure for operation which will subsequently increase construction and maintenance cost. Also, a lighter medium is much easier to replace than a heavier one. Therefore, in terms of construction, synthetic fiber is the most practical followed by woodchip and pot gravel.

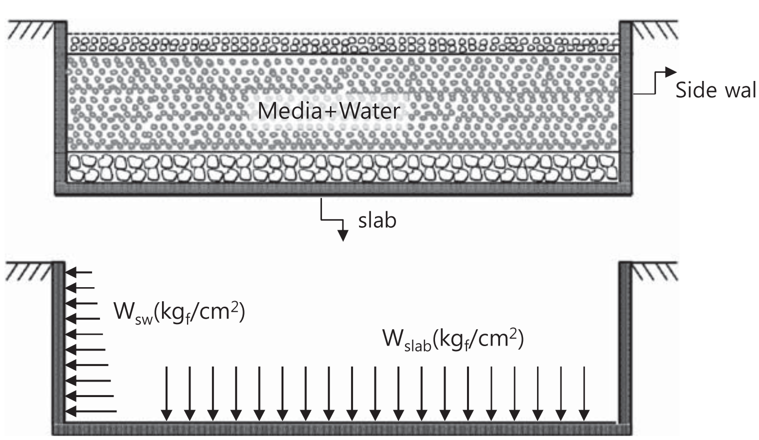

Fig. 5. The schematic diagram of the load from filter media layer.

4. Conclusions

The performance of four different types of filter media, which were employed as the main media in a group of column VF stormwater wetlands, was evaluated in eight different aspects. The evaluation results revealed useful suggestions for the design of VF stormwater wetlands:

- Regardless of the media type, all groups of wetlands were found to be efficient on TSS removal (more than 80%). Except for woodchip, all the media showed efficient reduction on organic matter, while woodchip was most effective on TN removal (about 40%). In addition, synthetic fiber and pot gravel displayed higher efficiency on TP removal, 75 and 65%, respectively.
- Based on the BET test, pot gravel displayed the highest adsorption capacity followed by volcanic stone, but their disposal cost may be a burden when the adsorption capacities are exhausted.
- Relatively, woodchip showed the largest grain size with 66% porosity. Pot gravel had a larger grain size than volcanic stone and they had a similar porosity of approximately 50%. Synthetic fiber had a uniform pore size and the highest porosity of 89%.
- Synthetic fiber was only capable of surface filtration due to its small and uniform pore size, while in-depth filtration was expected in the other media.
- The densest root and largest biomass in the woodchip wetland implied that it was most suitable for plant growth. On the contrary, less nutrient and poor water-holding capacity in synthetic fiber caused the poorest growth in synthetic fiber. The plants in pot gravel and volcanic stone showed approximate and intermediate biomass.
- In the operation period, some substrates such as organic matter and phosphorous, were leached out from woodchip and volcanic stone, respectively, due to their nature. Meanwhile, ammonia was released from synthetic fiber in the acclimation phase.
- As the main media, synthetic fiber had the highest cost with 14,059 $\$/m^3$, followed by volcanic stone 260 $\$/m^3$, pot gravel 132 $\$/m^3$ and woodchip 57 $\$/m^3$.
- Finally, the woodchip layer brings a bottom load of 325 kg/m^2 to the wetland, which is close to the pot gravel layer with 360 kg/m^2 and synthetic fiber layer with 311 kg/m^2. Due to the greater density and proper porosity, the volcanic stone layer shows the largest load of 608 kg/m^2.

In summary, taking all the evaluation parameters into consideration, woodchip and pot gravel are the optimal media suitable for the VF stormwater wetland. Further, the former is more cost-efficient than the latter due to the lower purchasing cost and easier disposal. Volcanic stone is also a considerable option if the cost is acceptable and there is no obstacle for constructing strong structure to meet the heavier loading. However, synthetic fiber should be neglected because of the surface clogging, poor condition for plant growth and expensive cost.

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