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Analyses of Bioretention Systems for Removal of Stormwater Pollutants

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ABSTRACT

Stormwater transports directly into rivers eroded soil, animal wastes, pesticides, fertilizers and other potential pollutants. Bioretention is often designed to capture and treat it using the natural properties of soil and plants. However, selection of appropriate media structure and plants need to be adequately studied. This study investigated the performance of bioretention system in removing stormwater pollutants using Dracaena, a local plant, also called Song of India Plants. Physical model of three Columns A, B and C were developed having five layered filter media of different configurations whose materials were analyzed to meet the design standards. The plants were introduced into Columns A and C leaving out B as control experiment. The quality parameters were determined before and after treatments at ages 10, 20, 30 and 40 days when Dracaena plants were introduced into bioretention models. The results showed that the bioretention model drastically improved stormwater quality by reducing values of electrical conductivity, total coliforms (TC), fecal coliforms (FC), total suspended solids (TSS) and biochemical oxygen demand (BOD) as compared to the tested raw stormwater samples. The filter media in both Columns A and C substantially reduced the pollutant levels to standard discharge limits for all parameters tested such as TSS, TC, FC, BOD and nitrates. BOD fell within the recommended standard after 20 days of treatment in Column C with considerable reduction in TC and FC by 68.9% and 75.4% respectively when compared to raw stormwater sample. However, Column C completely removed TC and FC at 40 days which are pathogen indicators in wastewater. This study would be useful to the stakeholders for sustainable stormwater treatment and management.

Keywords: bioretention, stormwater, pollutants, *Dracaena reflexa*, total dissolved solids.

INTRODUCTION

The 21st century is characterized with high rate of conversion of rural to urban areas with a number of impacts on the human populace. One of such impacts is increasing demand for water leading to excessive withdrawal of freshwater sources to meet the demand and increased volume of solid waste generation. In urbanization process, large impervious areas are created by buildings and pavement surfaces that alter hydrological characteristics of the watershed (Chithra *et al*., 2015; Schoener, 2018). The alteration results in flooding of downstream reaches, river bank erosion and deteriorating water quality due to increasing sediment loads, fecal matters, nutrients, and heavy metals, and a decline in aquatic biota (Van Meter *et al*., 2016; Hupp *et al*., 2009). Literature revealed that anthropogenic activities could change the landuse pattern with increased pollutants generation, increased mobility and transportation of pollutants due to heavy stormwater (Muhammad *et al*., 2015; Husna *et al*., 2019) and thus, degrades waterbodies downstream (Izegaegbe *et al*., 2022, Abdulkadir *et al*., 2017). In developing countries, some rural communities relied largely on streams, rivers and ponds as principal and/or alternative sources of drinking water which are being polluted by indiscriminate disposal of sewage, industrial waste, etc. Extensive review of literature indicated the presence of numerous physical, chemical and microbiological pollutants in stormwaters (Huber *et al.*, 2016; Ahmed *et al.*, 2019). Some typical pollutants are floating solids, nutrients, organic compounds, heavy metals, pesticides or herbicides from agricultural practices, polychlorinated biphenyls, phenols and cresols, among others (Rajak *et al.*, 2024). In a study conducted by Son and Kwon (2022), it was established that the volume of rainfall, watershed area and the percentage of impervious area are the predictors of nutrient concentrations and pollutant loads. The landuse pattern and the occurrence of stormwater runoff have been identified as factors causing microbiologically water quality degradation of surface water (Hong *et al.*, 2009).

In Uganda, stormwater pollution plays a major role in deterioration of surface water quality contributing to eutrophication and impairment of freshwater in the lakes, rivers and wetlands. Concentration of nutrients such as phosphorus and nitrogen encourage eutrophication processes which deplete oxygen availability to the aquatic lives for survival (Bratieres *et al.*, 2008). Furthermore, reckless uses of pesticides and fertilizers on farmlands, untreated wastewaters from manufacturing industries and toxic substances from motor vehicles impend on water quality, kill fish and other aquatic animals. To date, the Ugandan government has developed a number of policies to regulate landuse changes and mitigate its environmental impacts. For instance, sector-wide approach to planning for water and sanitation, National Wetlands Policies, Environmental Impact Assessment Resolutions, National Environment Management Policy, National Environment Statute, National Land Use Policy, etc. In spite of these laws, stormwater generated is continuously discharged towards the streams and rivers downstream in urban areas without being treated. A bioretention is a stormwater best management practices (BMP) designed to capture and treat stormwater using the natural properties of soil and plants to remove the pollutants (Lucas and Greenways, 2008; Asleson *et al.*, 2009; Zinger *et al.*, 2021). It composed of soil media arranged in layers and vegetation designed for pollutants removal while retaining and detaining stormwater volumes (Muhammad *et al.*, 2021). The water effluents exfiltrated into underlying or collected in the underdrain systems, sub-soil perforated drain to downstream receiving water bodies (Brown and Hunt, 2011; Husna *et al.*, 2019). Baek *et al.* (2020) highlighted that bioretention is one of the leading low impact development practices for modification of hydrologic impacts of urbanization and improving stormwater quality. Thus, this study is aimed at investigating the efficiency of bioretention system in the removal of stormwater pollutants using *Dracaena reflexa*, a local plant popularly known as Song of India Plants.

MATERIALS AND METHODS

Design of bioretention model

This section describes how bioretention model was developed for the treatment of stormwater samples. The detailed of constituents or composite materials (such as plant species, coarse aggregates, fine aggregates and stone mulch) used are provided in the following sub-sections.

Preparation of materials used in the model

Plant species. In a study by conducted by National Parks Board and the National University of Singapore – Delft Water Alliance, *Dracaena reflexa* was one of over 30 plant species selected, screened and tested their suitability for application as vegetation in bioretention systems. Different factors were considered including plant growth form, water requirements, plant density, safety considerations, and pollutant removal. Similarly, Terras-Soler (2016) listed *Dracaena reflexa* as one of the 87 plant species in Caribbean suitable for rain gardens, bioswales and bioretention cell. William *et al.* (2015) also highlighted this plant species along with few other plants capable of Nitrate and phosphate removal in bioretention system. Meanwhile, dracaena is more available in most parts of the world including Uganda. However, there are very scanty studies that investigate the efficacy of this plant in bioretention for stormwater treatment. The plant species (Fig. 1) was used in Columns A and C, from which seeds were obtained from common nursery beds in the region. The seeds were planted into the small nursery bed for up to a total of 40 days. At ages 0, 10, 20, 30 and 40 days, the plants in Columns A and C were used for bioretention experiments. This allows the evaluation of performances of the plant at different ages of growth.

This plant was chosen because of its availability within the region. Common names for the plant are: Song of India. Plant growth form:

Figure 1. Song of India in a nursery bed

Shrub. Origin: South India, Ceylon Desirable plant features: Ornamental Foliage.

Coarse aggregates. The aggregate size was obtained through gradation (sieve) analysis to meet the design manual standards for bioretention system. The coarse aggregates of size (> 9.5 mm) were used in the Columns. More so, coarse sands of size 1.18–4.75 mm as described in Table 1 were also used. All the coarse aggregates were washed and dried before being placed in the columns.

Fine aggregates. The fine aggregates of size (0.063–1.18 mm) and coarse aggregates of size (4.75–9.5 mm) obtained through gradation analyses were used in the Columns setup of the bioretention system. All the materials used were obtained from Nyihanga, Kabale District, Uganda.

Stone mulches. The stone mulch of sizes 4.75 to 6.0 mm was used in Column C. The stone mulches were preferred over the organic mulch due to decomposition of organic mulches in the presence of nutrients and out-compete with the soil nutrients which makes the plants weak. These mulches, obtained from Kekubo in Kabale District, were washed, dried and sieved before being introduced in Column C for stormwater treatment.

Stormwater sampling. Composite technique of sample collection was adopted due to continuous and heterogeneous stormwater flowrate and pattern. This was achieved by collecting a fixed volume at equal time intervals, of every 10 minutes at about 15 cm deep below stormwater surface. The individual samples were then mixed together to give one representative sample. The volume of samples collected were enough to conduct bioretention stormwater treatment and subsequent physical, chemical and biological water quality tests.

The sampling bottles were rinsed many times with the same stormwater to get rid of any potential contamination before sampling. Stormwater samples for determining physical and chemical parameters were collected using high-density polyethylene (HDPE) sample bottles to maintain its temperature and the original quality at the time of collection. For the coliform bacteria, borosilicate glass bottles, as recommended by (APHA, 2017) were used for sample collection. Each filled glass bottle was wrapped in silver foil, providing an additional layer of protection against light and temperature variations.

The samples collected in the field were conveyed to the Laboratory of South Western Umbrella Kabale-Uganda in shortest time possible to avoid deterioration in their quality. Some in-situ tests such as pH, temperature and color were performed on the site immediately after the samples collection and observations were recorded. These were done to minimize the potential chemical and biological interferences during the experimentation.

Preparation of filter media.

The technical manuals for the design of bioretention specified by “Water by Design” (2014) was followed coupled with particle size (gradation) analysis of fine and coarse aggregates in line with BS 812: Part 103.1 (1985). After preparation of materials, the media structure was arranged according to layers’ constituent and arrangement shown in Table 1 for both Columns B and C. Column B appeared as a conventional sand filter bed which served as a control experiment in order to evaluate the performance of the bioretention system.

Design, construction and treatment of stormwater in bioretention columns

Bioretention column models were constructed using 102 mm diameter, clear PVC pipes cut into 1050 mm lengths. One end of the pipe was wrapped with a porous filter to enable the passage of treated storm water to the collection container as shown in Figure 1. Three Columns A, B and C were constructed in this manner and housed in a heavy-duty wooden workbench. The procedures are presented as follows:

a) the sterile and compact filter media varied in grain sizes and configurations for the different columns as shown in Table 1. Each layer was filled according to the bioretention design in Figure 2;
b) a 250 mm deep ponding area was left unfilled in the topmost portion of the columns;
c) the selected plants were watered regularly and permitted to grow before experimentation commenced. Tap water was used for watering only after being left in an open bucket (to promote residual chlorine diffusion) for at least one day;
d) after 0 –, 10 –, 20 –, 30 – and 40 – days age of the *Dracaena reflexa* plant, the collected stormwater samples were poured carefully into the Columns and clean collection containers were placed under the Columns to receive the treated effluent;
e) the experiment was monitored and the time required for the water to pass through the filter media recorded to evaluate flowrates through bioretention setup;d
f) all stages of the experiment took place indoor at a temperature from 25 °C to 30 °C. At ages 10, 20, 30 and 40 days of *Dracaena reflexa* plant for stormwater treatment in the model, effluents in each container were sampled using clean sampling bottle for water quality analyses. The analyses were carried out at South Western Umbrella of Water and Sanitation Laboratory, Ministry of Water and Environment, Uganda.

Stormwater quality determination and analysis

Stormwater was sampled according to South African Bureau of Standards (SABS) 241-1971 following the sampling method MA4. The quality analysis was carried out to identify various physiochemical parameters of the stormwater and compare to the National Environment Management Authority (NEMA) standards. All the on- and off-site tests were conducted in accordance to the standard operating procedures stated in the national water quality handbook of Uganda (NWSC, 2015) adopted from reputable standards. The stormwater quality parameters tested for were temperature, pH, EC, TDS, TC, TSS, Chlorides, Sulfates, Nitrates, Phosphorous, BOD, Turbidity, color, Oil and Grease (OG) and Fecal Coliform (FC). Membrane filtration conducted according to standard method (APHA, 2017) was used to measure TC and FC while other standard measuring techniques were adopted for other parameters.

Then, the stormwater samples were treated in bioretention of different configuration for pollutant removal. The levels of treatment achieved were evaluated by testing the physiochemical quality of the treated effluent. The physicochemical parameters were used to establish the water quality index analysis (WQI) of the raw stormwater sample. WQI was estimated using weighted arithmetic index method in Equation 1.

$$WQI = \frac{\sum W_i Q_i}{\sum W_i} \quad (1)$$

Table 1. Layer constituents and arrangement in the columns

Layers	Thickness	Column A	Column B	Column C
Layer 1	200 mm	Stormwater sample	Stormwater sample	Stormwater sample
Layer 2	200 mm	Song of India plants	Fine sand (0.063–1.18 mm)	Black soil with mulch and Song of India plants
Layer 3	200 mm	Sandy loam soil	Coarse sand (1.18–4.75 mm)	Fine sand (0.063–1.18 mm)
Layer 4	200 mm	Coarse sand (1.18–4.75 mm)	Coarse aggregates (AASHTO M 43) (4.75–9.5 mm)	Coarse aggregates (AASHTO M 43) (4.75–9.5 mm)
Layer 5	200 mm	Coarse aggregates (> 9.5 mm)	Coarse aggregates (> 9.5 mm)	Coarse aggregates (> 9.5 mm)

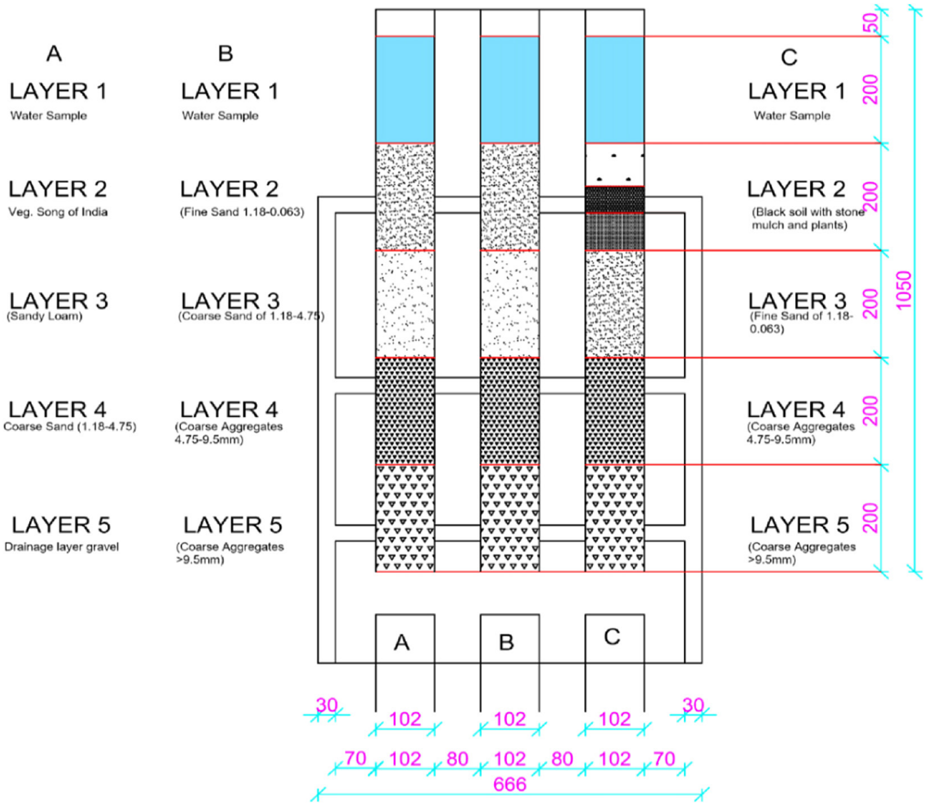

Figure 2. Designed bioretention model

where: *Wi* – relative weight or unit weigh, *Qi* – qauality rating scale, which is calculated as $Q_i = \frac{C_i}{S_i} \times 100$, *Ci* – mean concentration of each parameter in the water sample, *Si* – recommended standard.

RESULTS AND DISCUSSION

Raw stormwater quality analysis

The quality parameters for raw stormwater samples were tested in the laboratory to determine the level of pollution. The test results obtained is presented in Table 2. Preliminary evaluation indicated no presence of heavy metals. Measured stormwater quality parameters showed that all the tested parameters met the recommended discharge standard of NEMA Uganda (NEMA, 2020) except pH, TC, TSS, Nitrates, BOD and FC. A pH value of 4.2 obtained indicated the stormwater is acidic which could be attributed to humic acid from decaying organic matters such as corn, combs, leaves, cassava peels (Izegaegbe *et al.*, 2022). This lower pH value than the recommended could enhance the corrosive characteristics of the water (WHO, 2007). High concentration of TSS indicates presence of organic and inorganic matters (Alvado *et al.*, 2021), which is objectionable as it impedes photosynthetic processes, affects osmoregulation of freshwater organisms and make such water unfit for irrigation and industrial purposes (Oram 2014; Boyd, 2019). Furthermore, higher concentration of BOD reduces availability of dissolved oxygen to aquatic animals due to eutrophication process (Akkoyunlu and Akiner, 2012; Chapra *et al.*, 2021). Municipal waste such as soaps and detergents, fertilizer runoff, decaying plant and animal materials in rivers responsible for the high nitrate concentration. Presence of untreated human sewage, animal waste from agricultural practices responsible for high TC and FC concentration. The overall WQI of the raw stormwater sample was estimated and obtained as 63.2, which belong to Class C and classified as being poor according to Tyagi *et al.* (2013). Analysis of pollution index having index value of 1.89 that falls between 1.01–2.00 showed that the raw sample is moderately polluted (Zhaoa *et al.*, 2012).

Stormwater treatment in bioretention columns

Surface water impairments from pathogens and total suspended solids were the major problems in waterways throughout Uganda and some other developing countries. TC counts are commonly used as an indicator of pathogens presence in stormwater. These pathogens originated from human wastes, livestock and wild animals, untreated sewage discharge, agriculture and stormwater runoff (Hong *et al*., 2010). Hence, these pollutants need to be reduced in stormwater to mitigate the spread of disease-causing microorganisms. The test results in Table 2 showed TC value of 90 CFU/100 ml which is very far from zero value recommended by NEMA. Therefore, raw stormwater samples were treated in the constructed bioretention models. Unlike traditional detention basins, bioretention systems are meant to manage water quality in addition to quantity and peak flow rates (Weerasundara *et al*., 2016). The stormwater samples were treated in bioretention Columns A, B and C of different configuration as described in Table 1.

Stormwater quality parameters after treatment

The raw stormwater was treated in Columns A, B and C in which Column B serves as a control because its constituents were just like conventional sand filter bed. After the preliminary experimental evaluation of raw water quality parameters (such as TC, TSS, Nitrates, BOD and FC) which previously fell outside the recommended NEMA standards were then re-evaluated after samples were filtered through Columns A, B and C. The results were compared with raw stormwater quality and the recommended standards as presented in Table 3.

From Table 3, stormwater quality parameters (i.e., TC, TSS, Nitrates, BOD and FC) reduced when stormwater samples were treated in Columns B and C. Column B, being a conventional sand filter bed (used as a control experiment) reduced only TSS and Nitrates to fall within the recommended standards for stormwater. The level of stormwater treatment in Column B was quite close to that of Column C at 10 days of treatment. However, BOD of 43 mg/l fell within the recommended standards after 20 days of treatment in Column C with considerable level of reduction in TC and FC by 68.9% and 75.4% respectively when compared to raw stormwater samples. Higher BOD concentration in waterbodies may be due to decomposition of organic matters (Kumari *et al*., 2013) which would encourage eutrophication process and results in insufficient oxygen availability to the fish (Chapra *et al*., 2021). After 30 days, there were further reductions in TC and FC to 22 and 5 CFU/100 ml respectively and eventually removed 100% in Column C at 40 days. It was observed that Column C had the optimal arrangement of filter media to fulfill the primary aim of the study. The recorded time required for the stormwater sample to pass through the Column C (0.87 hrs) was used to calculate the hydraulic

Table 2. Raw stormwater quality parameters

Parameters	Units	Quality parameters	NEMA discharge standards	WHO limits (Maximum)
Temperature	°C	22	20–35	27–40
pH	-	4.2	5.5–8.5	6.5–9.2
Electrical conductivity	us/cm	600	<1500	500
TDS	mg/l	445	<1500	500
Total coliforms	CFU/100ml	90	0	0
TSS	mg/l	208	< 100	25–30
Chlorides	mg/l	190	< 250	250
Sulphates	mg/l	320	< 500	400
Nitrates	mg/l	25	< 20	10
Phosphorus	mg/l	3.65	< 10	10
BOD	mg/l	74	< 50	0.05
Turbidity	NTU	250	< 300	NA
Oil and grease	mg/l	5	< 10	NA
Fecal coliforms	CFU/100ml	65	0	0

Table 3. Water quality parameters of columns A, B and C

Stormwater quality parameters	Units	Raw storm water	Column A	Column B	Column C				NEMA discharge standards
			40 days		10 days	20 days	30 days	40 days	
TC	CFU/100ml	90	26	80	46	28	22	0	0
TSS	mg/l	208	45	50	86	44	30	15	<100
Nitrates	mg/l	25	18.54	19	19.52	18	15.55	12.4	< 20
BOD	mg/l	74	40	64	66	43	18	15	< 50
FC	CFU/100ml	65	12	52	46	16	5	0	0
EC	us/cm	1600	550	1540	1000	940	580	500	< 1500
TDS	Mg/l	1745	321	1600	840	778	244	210	< 1500
OG	Mg/l	15	3.58	12	5.16	3.44	3.21	3.18	< 10

retention time. This is important because as stormwater passes through a treatment column, it must stay in the column for the necessary period of time in order to be adequately treated. The hydraulic retention time of the bioretention Column C setup was observed as 0.87 hours.

General performance of columns A and C

The electrical conductivities of the treated stormwater in Column A and C were respectively 550 and 500 µs/cm which were below 1500 µs/cm acceptable for water discharge standards. The total dissolved solids were respectively reduced to 321 and 210 mg/l which are acceptable for the discharge limit of set as 1500 mg/l. In Column A, fecal coliforms (E. *coli*) were also reduced to 12 counts/100 ml at 40 days which is not acceptable for the limiting value of 0 counts/100 ml. However, Column C recorded a reduction to 0 counts/100 ml which is acceptable for the limiting value of 0 counts/100 ml.

The total coliforms after treatment in Column A were reduced to 26 counts/100 ml but Column C completely reduced it to acceptable 0 counts/100 ml at 40 days. Both Columns A and C recorded a remarkable reduction in total suspended solids. However, the latter had a 100% removal. The arrangement of filter media in both Columns substantially reduced the pollutant levels of stormwater to standard discharge limits for all water quality parameters tested. However, Column C completely removed the total coliform count and fecal coliforms. By this, increased risk of water related gastrointestinal and respiratory illnesses highlighted in some epidemiological studies would have been mitigated Hong *et al*., 2009; McGinnis *et al*., 2018).

Performance of column C at both laboratory and field scale

The filter arrangement in Column C was implemented on field scale due to its unique performance in removal of TC and FC. This was carried out to assess the efficiency of filter media similar to Column C on the field scale when compared to the NEMA standards for the stormwater treatment. The results of the analyses in Table 4 indicated that filter media configuration continued to perform optimally on field scale with further improvement in stormwater quality parameters which include TDS,

Table 4. Water quality parameters for column C on both laboratory and field scales

Parameters	Units	Raw water	Column C on laboratory scale at 40 days	Column C on field scale at 40 days	NEMA discharge standards
TC	CFU/100ml	90	0	0	0
TSS	Mg/l	208	15	16	< 100
Nitrates	Mg/l	25	12.41	12.00	< 20
BOD	Mg/l	74	15	15	< 50
FC	CFU/100ml	65	0	0	0
EC	us/cm	1600	500	300	< 1500
TDS	Mg/l	1745	210	199	< 1500
OG	Mg/l	15	3.18	2.03	< 10

TC and FC. This would assist in arresting coliform bacteria which is often at peak after a rain event and are mostly higher in urban settlements (Hong et al., 2009). If bioretention is implemented in urban areas, it would mitigate contamination of the rivers. The treated stormwater in bioretention can be used for irrigation, washing bays and eliminate the water crisis challenges in urban areas. It was highlighted that there is no serious limitation to use of *dracaena reflexa* in bioretention systems because it is capable of resisting harsh weather conditions (William *et al*., 2015; Terras-Soler, 2016). However, if used in urban setting, it only requires maintenance after every rainy season to improve its infiltration capacity.

CONCLUSIONS

Stormwater transports eroded soil, animal wastes, litters, salts, pesticides, fertilizers, oil and grease and other potential pollutants which flows directly into the streams and rivers. This impairs the stream water quality and thereby causing a decline in aquatic biota. The preservation of healthy waterbodies is linked to its physiochemical properties and biological diversity. Identification and pre-treatment of stormwater runoff is very crucial for protecting public health from diseases-causing pollutants and maintaining the environmental regulations. A bioretention is one of the stormwater best management practices (BMP) designed to capture and pre-treat the runoff using the natural properties of soil and plants to remove pollutants. In this study, quality assessment of the raw stormwater samples revealed that all the tested parameters were within the NEMA standards except TC, TSS, Nitrates, BOD and FC. The BOD of the stormwater samples reduced to fall within the recommended standard after 20 days of treatment in Column C with considerable level of reduction in TC and FC by 68.9% and 75.4% respectively when compared to raw stormwater. The arrangement of filter media in both Columns A and C substantially reduced the pollutant levels of stormwater to standard discharge limits for all water quality parameters tested such as TSS, TC, FC, BOD, and nitrates. However, filter media in Column C completely removed the total coliform count and fecal coliforms at 40 days which are pathogen indicators in wastewater samples. This study provided basis for developing a bioretention system with guidelines on the media structure arrangement, implementation and effectiveness of plants in the system. If implemented, bioretention would mitigate contamination of the rivers and streams in urban areas. The study would be useful to the stakeholders for sustainable stormwater and environmental management.

Further studies could be conducted for treatment of stormwater beyond 40 days age of *dracaena reflexa*. Other plant species such as *Croton Lobatus*, *Cadiaeum variegatum*, *Hamelia axillaris*, etc, recommended for use in bioretention by Terras-Soler (2016) could also be investigated in future studies.

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