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Microplastic Removal from Road Stormwater Runoff using Lab-scale Bioretention Cell

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Abstract

Microplastic removal from stormwater runoff from roads is necessary to reduce the effect of microplastic pollution in water bodies. Bioretention is a potential technology to remove microplastics in stormwater runoff from roads. A lab-scale experiment was conducted to determine the efficiency, effect on vegetation and discharge variation, and the kinetics of microplastic removal from stormwater runoff from roads using a bioretention cell. The experiment was done using an artificial sample based on visual characterization of stormwater runoff from highways, commercial, and residential roads. The vegetations that were examined were Vetivera sp. and Hibiscus sp. The operational discharge was varied based on rainfall intensity categories. The result showed that the removal efficiency was in the range of 92.4 to 99.3% with a mean of 97.2%. Statistical analysis ($\alpha = 5\%$) showed that variation in vegetation and discharge had no significant effect on microplastic removal using bioretention. The first-order kinetic analysis showed that the kinetic removal constant of the bioretention with Vetivera sp., bioretention with Hibiscus sp., and bioretention without vegetation was 0.0356, 0.034, and 0.0327, respectively. These results indicate that bioretention with Hibiscus sp. removed more microplastics at greater depths than with Vetivera sp.

Keywords: *bioretention; microplastic; removal; road; stormwater runoff; vegetation.*

Introduction

Microplastics have been identified in the aquatic environment, ranging from rivers to coastal areas [1-4]. It has even been reported that microplastics have been ingested by marine organism, such as wild clams [5]. The major pathway of microplastics into aquatic ecosystems is stormwater, including stormwater runoff from roads [6]. Research by Lange *et al.* [7] has shown that 20- to 100-µm sized microplastic particles were abundant in highway stormwater runoff with varied concentrations from 42 to 85777 particles/L and a median of 230 particles/L. Rosso *et al*. [8] reported that stormwater runoff from highways contained 5- to 100-µm sized microplastic particles with varied concentrations from 11932 ± 151 to 18966 ± 181 particles/L. Vogelsang *et* al. in [9] showed that major sources of microplastic in road dust in Norwegia were tire wear, polymer-modified bitumen, and road marking paint.

When rain occurs, dust pollutants that contain microplastics will be carried away by stormwater runoff from the roadside to the drainage system. Most stormwater runoff ends up in the aquatic environment without any prior treatment. Microplastics that enter the marine environment from land, particularly through surface runoff, have a major impact on marine organisms [10]. Research by Tian *et al*. [11] has shown that the highly toxic quinone transformation product of N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenedinamine (6PPD), a ubiquitous antioxidant that is globally used in tire rubber, is carried by stormwater runoff from roads into the creeks on the U.S. West Coast, causingacute mortality among coho salmon. Therefore, it is necessary to remove microplastics from stormwater runoff water from roads to reduce the impact of microplastic pollution in water bodies.

Research on the removal of microplastics from stormwater runoff from roads has been carried out, including removal using bioretention cells [12], gross pollutant traps – bioretention and sand filters [13], filtration systems

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with sand and biochar [14], surface runoff water retention ponds [15], and rain gardens [6]. However, previous studies on microplastics on stormwater runoff water from roads and their removal have only been carried out in sub-tropical and cold climates. Therefore, it is necessary to conduct a similar study to identify the microplastic content in stormwater runoff water from roads and the removal potential in Indonesia, which are under different conditions. This study aimed to determine the efficiency of microplastic removal using bioretention cells and examine the effect of vegetation and discharge variation on microplastic removal using bioretention cells. Bioretention is a low-energy stormwater mitigation system that can improve water quality and reduce peak flow of stormwater runoff [6]. It also has the potential to remove microplastics from stormwater runoff through physical filtration. Several studies have shown that bioretention cells could remove microplastics up to 84 to 100% [6,7,12,17-19]. In addition, bioretention has numerous other advantages, including the ability to be used for self-irrigation and fertillization, provision of habitats and protection for biodiversity, integration with local urban designs, a higher level of amenity than conventional drainage systems, and cooling of the micro-climate around the system [16].

Methodology

Field Sampling

Sampling of stormwater runoff in the field was carried out using the grab sampling method. Sampling was carried out on the side of the road when rain occurred before runoff water entered the drainage channel. Sampling of stormwater runoff was carried out on the Cipularang Toll Road to represent highways, Merdeka Road (in front of the Bandung Indah Plaza shopping center) to represent commercial roads, and Arcamanik Endah Road to represent residential roads. Sampling from each location was carried out at three different rainfall events in the period of July to October 2022. The volume of samples taken at each location was 2 L.

Characterization of Microplastic in Stormwater Runoff from Roads

Microplastic analysis in this study refers to the laboratory method manual for microplastic analysis released by the National Oceanic and Atmospheric Administration (NOAA) in 2015 [20] and similar previous studies [7,12,14, 15,21,22]. Pre-treatment of microplastic samples was carried out to separate microplastic from water samples to facilitate the quantification and identification of microplastics. Pre-treatment was carried out by the density separation method using $ZnCl_2$ 1.5 g/cm^3. $ZnCl_2$ with a higher density will increase the density of the sample, causing microplastics with density lower than 1.5 g/cm^3 to float while other particles settle. Furthermore, the sample was treated by sieving using a nylon filter with a pore size of 25 µm and filtration using glass microfiber filter paper GF/C 4.5 mm (1.2-µm pores).

Quantification and identification of the color, shape, and size of microplastics were carried out visually using an Olympus CX-31 light binocular microscope with 40x and 100x magnification. Color and shape categorization was carried out using the Standardized Size and Color Sorting (SCS) System method compiled by Crawford in 2014 [23]. The size of the microplastics was divided into four categories with size ranges of 25 to 125 µm, 125 to 300 µm, 300 to 1000 µm, and 1000 to 5000 µm based on the filter size available at the Water Quality Laboratory of Environmental Engineering ITB and refers to Lange *et al*. [7] and Pankkonen [14]. However, quantification and identification of microplastics using the visual method is subjective and may lead to overestimation or underestimation of certain types and colors of microplastics [24]. Therefore, some criteria from Crawford & Quinn [23] and Hidalgo-Ruz *et al*. [25] were used to prevent misidentification and misestimation, i.e., no cellular or organic structures are visible, fibers should be equally thick over the entire length, and the particle must present clear and homogenous colors. Tire wear and asphalt bitumen have similar visual characteristics that make them difficult to distinguish. Therefore, the visual method was enhanced with a tactile test. Rubber particles are elastic, so they will regain their shape after being squeezed, whereas bitumen particles will remain compressed [21].

Bioretention Cell Experiments in the Laboratory

The experiment was carried out in the laboratory using a cylindrical column made of PVC with a diameter of 30 cm and a height of 120 cm. Three bioretention columns were installed in the ITB Environmental Engineering greenhouse so that they could be directly exposed to sunlight. Each column was filled with filter media with a thickness of 60 cm, a transition zone with a thickness of 10 cm, and a drainage zone with a thickness of 20 cm. At the top of the bioretention zone, there was a ponding zone with a thickness of 30 cm. Sampling of water was carried out at the influent (before the water passed through the medium), at depths of 40 cm, 60 cm, 80 cm, 100 cm, and 120 cm from the column surface (3 outlets on the filter media, 1 outlet at the bottom of the transition zone, 1 outlet at the bottom of the transition zone, and 1 outlet at the bottom of the drainage zone). The design of the bioretention column is shown in Figure 1.

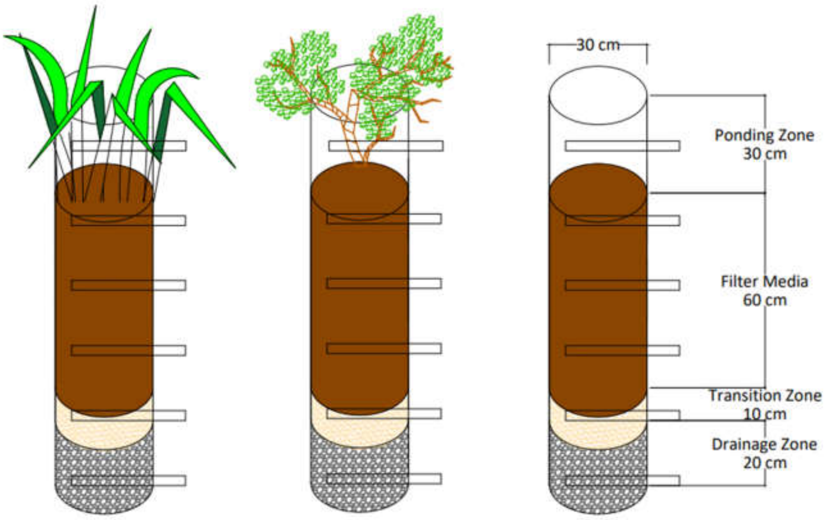

Figure 1 Design of the bioretention column.

The filter media in the bioretention cell system consisted of a mixture of topsoil, medium sand (20 to 30 mesh), and compost. The composition of the mixture was 25% topsoil, 60% medium sand, and 15% compost by volume. The effective size, uniformity coefficient, and porosity of the filter media were 0.294, 2.35, and 0.55. The medium used for the transition zone was coarse sand (14 to 20 mesh) to prevent migration between the bottom filter media and the drainage zone. The media used for the drainage zone was gravel (4 to 8 mesh). Bioretention column A was covered with vetiver (*Vetivera zizanioides*), bioretention column B was covered by *Hibiscus* plants (*Hibiscus rosa—sinesis*), while bioretention column C was not covered with plants.

Artificial samples were made using scraped vehicle tires to represent the majority of colors and shapes identified from microplastic characterization of the stormwater samples, which were black fragments. The microplastics were sieved using 120 and 40 mesh to obtain microplastics with sizes ranges of 25 to 125 µm and 125 to 4750 µm. The size ranges were determined based on the characterization of the microplastics in the stormwater runoff sample. The analysis revealed that the majority of microplastics were within the size range of 25 to 125 µm, while the number of larger particles was lower. The artificial microplastic was mixed into a tap water sample based on the previously determined characteristics of microplastics found in stormwater runoff. The microplastic was proportioned at 98% for sizes ranging from 25 to 125 µm and 2% for sizes ranging from 125 to 4750 µm. The amount of artificial microplastic added to the water was determined by weight, while the concentration of particles per liter was measured at the bioretention inlet. The operational discharge for the bioretention system was determined based on rainfall intensity (I), duration of rain (t), coefficient of surface runoff (C), and catchment area (A), based on the calculation of runoff discharge using the rational method shown in Eq. (1).

$$Q = 0{,}00278CIA \tag{1}$$

with Q as runoff discharge (m^3/sec), I as rainfall intensity during concentration time (mm), C as runoff coefficient, and A as catchment area (ha). The rain intensity was varied based on the rainfall category used by the Indonesian Agency for Meteorological, Climatological, and Geophysics (BMKG), which is 10 mm/day for the light rain category, 35 mm/day for the moderate rain category, and 75 mm/day for the heavy rain category. The intensity of rainfall expressed in units of mm/hour is calculated by the equation from Monobe:

$$I = \frac{R_{24}}{24}\left(\frac{24}{t_c}\right)^{\frac{2}{3}} \tag{2}$$

with R_{24} as the annual maximum daily rainfall for a return period of t years, and t_c as the concentration-time (hours). The concentration-time used for each running process was 30 minutes. The runoff coefficient (C) used was the runoff coefficient value for the category of asphalt road surface properties based on Regulation of the Minister of Public Works of the Republic of Indonesia No. 12 of 2014 regarding the Implementation of Urban Drainage Systems, which is 0.825. The guidelines for adopting a runoff bioretention system in Australia recommended the area of the bioretention system to be 2% of the impermeable catchment area [26]. The operation of the bioretention column was carried out to examine the variations for two parameters, plant and discharge variation.

Data Analysis

The data collected from the bioretention experiment was calculated to determine the efficiency and was analyzed using statistical and kinetics analysis. The removal efficiency was determined using the percentages of the concentration difference at the inlet and outlet per concentration in the inlet. Shapiro Wilk ($n < 50$) and Kruskal-Wallis ($n > 50$) normality tests were conducted. One Way ANOVA for normal distribution data and the Mann-Whitney test for non-normal distribution data were conducted to identify statistically significant differences in removal efficiency between variations. The level of significance was set at 5%. The statistical tests were carried out using SPSS. The removal kinetics was analyzed using the plug flow reactor kinetics model [27] and the filtration macroscope model [2] to obtain the first-order removal rate based on the following equation:

$$\frac{C_x}{C_0} = \exp(-kx) \tag{3}$$

where C_x is the outlet concentration, C_0 is the inlet concentration, k is the first-order reaction constant, and x is the distance. The first-order reaction constant was determined by linear regression of natural logarithmic concentration (y-axis) to distance (x-axis).

Result and Discussion

Microplastic Abundance in Stormwater Runoff from Roads

The results of the analysis on the nine samples tested in this study indicated that microplastics were identified in all samples of stormwater runoff water from the roads. The concentration of microplastics identified in each sample varied greatly. The lowest microplastic concentration was found in the second sample from a residential road (61 particles/L0). Meanwhile, the highest concentration was identified in the first sample from a commercial road (474 particles/L). The average microplastic concentration of all samples was 192.78 ± 132.72 particles/L. The comparison of microplastic concentrations in each sample is shown in Figure 2.

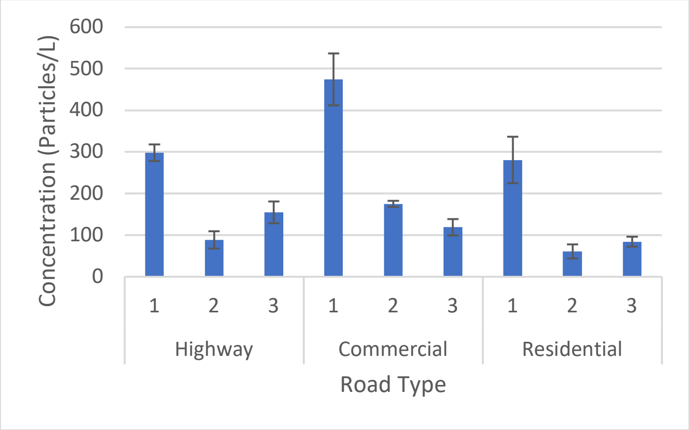

Figure 2 Comparison of microplastic concentrations in each sample.

Several studies have shown that the main sources of microplastics in surface runoff from roads are scraped-off vehicle tires, road marking paint, and polymer-modified bitumen [9, 21, 29]. In addition, microplastics in surface runoff from roads can also come from other plastic waste that is often found on the side of the road [29] or deposition of microplastic from the atmosphere onto the road surface [8, 12]. Based on the type of road, the highest average concentration of microplastics was the stormwater runoff from a commercial road, which was 256 ± 173.22 particles/L, the second highest average concentration of microplastics was found in the sample from a highway, which was 180.33 ± 97.35 particles/L, and the lowest average concentration of microplastics was found in the sample from a residential road, which was 142 ± 111.04 particles/L. The comparison of microplastic concentrations between types of roads was comparable with the research by Liu *et al.* [15], where the highest concentrations of microplastics were found in stormwater runoff water treatment ponds from commercial areas and the lowest concentrations were found in stormwater runoff water treatment ponds from residential areas.

The characteristic of microplastic identified in this study and the literature showed that the most likely source of microplastic in the stormwater runoff was tire wear. Moreover, the high concentration of microplastics in stormwater runoff from the commercial road occurred due to buildings and human activities that produce plastic pollution around the road. A lower concentration of stormwater runoff from residential roads corresponds to less human activities and traffic. Meanwhile, the only possible source of microplastics in stormwater runoff from highways is vehicle tires due to the lack of direct human activity around highways. Nevertheless, atmospheric deposition may contribute to the microplastic abundance in stormwater runoff from all roads.

The concentration of microplastics in stormwater runoff from roads was compared with data from research on microplastics in wastewater and other surface water systems in Indonesia. The comparison of microplastic concentrations in stormwater runoff, wastewater, and other surface water systems in Indonesia is shown in Table 1.

Table 1 Comparison of microplastic concentrations in stormwater runoff, wastewater, and other surface water systems in Indonesia

Sample	Microplastic concentration (Particles/L)	Reference
Stormwater runoff from roads	474 ± 62.2	-
Wastewater in Setiabudi Centralized WWTP	Influent : 17,1 ± 5,65 Effluent : 1.41 ± 0,01	[30]
Wastewater in Communal ABR WWTP	Influent : 434,67 ± 22,68 - 973,33 ± 37,87 Efluent : 81.67 ± 8.02 – 203.67 ± 12.01	[31]
Wastewater in Communal AUF WWTP	Influent : 636.33 ± 13.87 – 818.33 ± 18.77 Efluent : 88.67 ± 4.16 – 157.67 ± 4.04	[31]
Citarum River	57.4 ± 25	[32]

Table 1 shows that the average microplastic concentration in stormwater runoff from roads was lower than the average concentration of microplastics in wastewater from the influent of a communal WWTP but higher than the average concentration of microplastics from the effluent of a communal WWTP, influent and effluent of an urban-scale WWTP, and river water. This indicates that stormwater runoff from roads is potentially a main source of microplastic pollution in water bodies but so far has not been managed. Therefore, microplastic removal from stormwater runoff from roads is necessary.

Characteristics of Microplastics in Stormwater Runoff from Roads

Size Distribution of Microplastics in Stormwater Runoff from Roads

In this study, microplastic sizes were classified into four groups. Most of the microplastics were found in the size range of 25 to 125 µm with an average percentage of 87%. Meanwhile, the least microplastics were found in the range of 1001 to 5000 µm with an average percentage of 3%. The size distribution of microplastic particles from each sample is shown in Figure 3. The size distribution of microplastic particles in stormwater runoff samples from the highway, commercial roads, and residential roads showed that the most microplastic particles were present in the size range of 25 to 125 µm, namely 155.67 particles/L (86%), 222.67 particles /L (87%), and 127.5

particles/L (90%). The number of particles in the larger size categories (126 to 300 µm, 301 to 1000 µm, and 1001 to 5000 µm) was very small compared to that in the size range of 25 to 125 µm. This shows that microplastics in stormwater runoff from roads were dominated by the smallest microplastic size range.

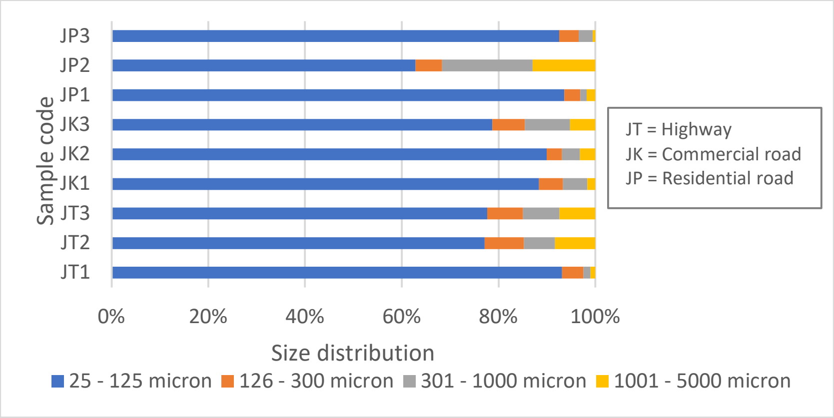

Figure 3 The size distribution of microplastic particles in stormwater runoff from roads.

The results of this study were compared to the research by Werbowski *et al*. [6], which showed that most microplastic particles were in the smallest size range (125 to 355 µm). The concentration of microplastics in this range was 2.5 times greater than the second-largest size category (>1 mm). Meanwhile, the lowest concentration of microplastics was found in the size range of 355 to 500 µm. The results of the study by Järlskog *et al*. [21] showed that the highest concentrations of microplastics and tire bitumen microplastics (TBMP) were found in the size range of 20 to 100 µm. This indicates that larger particles (≥100 µm) contain heavier particles that tend to settle faster than smaller similar particles [9].

Shape Distribution of Microplastic in Stormwater Runoff from Roads

The shapes of microplastic identified in the stormwater runoff from roads were fragments, fibers, and films. The dominant shape of microplastic found in all samples was fragments. The average concentration of fragment-shaped microplastics was 154.72 particles/L or 80% of all identified samples. The average percentage of microplastic in the form of fiber and film was 12% and 7%. The shape distribution of the microplastic from each sample is shown in Figure 4.

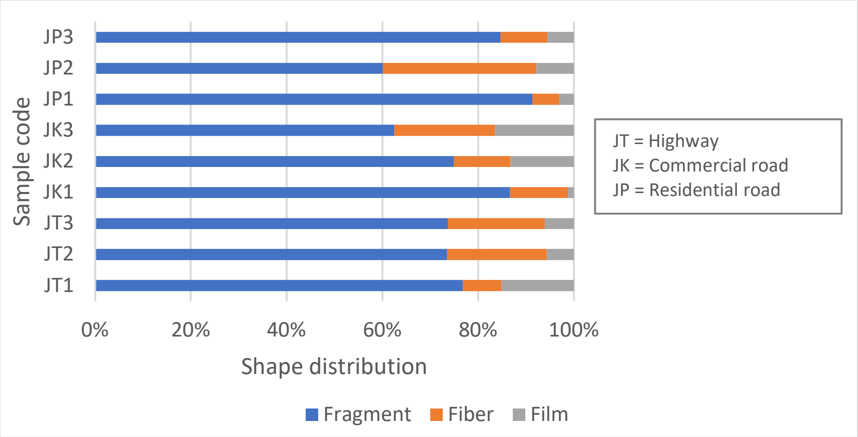

Figure 4 Shape distribution of the microplastics in stormwater runoff from roads.

Microplastic fragments found in stormwater runoff from roads were mostly black (84%) and 98% of microplastic fragments were in the size range of 25 to 125 µm. Compared with the research by Werbowski *et al*. [3], rubber fibers and fragments were the most common forms found in 12 sampling locations. The combination of fiber and rubber fragments accounted for ~85% of all particles in all samples, hard fragments accounted for as much as ~12%, and other categories found were spherical, foam, film, and fiber bundles, which totaled only ~2% of all particles.

Color Distribution of Microplastics in Stormwater Runoff from Roads

The colors of the microplastics identified in the samples of stormwater runoff from roads were black, orange, green, blue, red, pink, transparent, gray, yellow, brown, and purple. The most dominant microplastics color in all samples was black, with an average percentage of 73%. Meanwhile, microplastics with other colors had a fairly small percentage. The distribution of microplastic colors in each sample is shown in Figure 5.

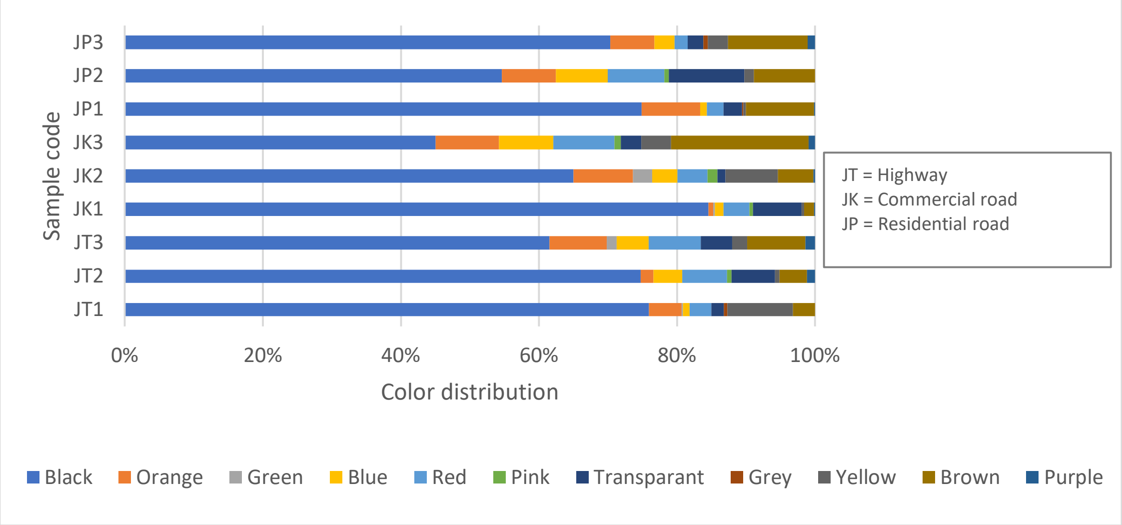

Figure 5 Color distribution of the microplastics in stormwater runoff from roads.

The results of this study were compared to the research by Werbowski *et al*. [6], where microplastics in stormwater runoff were dominated by black (55%). The results of research by Ziajahromi *et al*. [33] also showed that most of the microplastics identified in stormwater were black (>75%). The research by Roychand & Pramanik reported in [34] showed the results of observations with FTIR and SEM-EDS, indicating that the very large quantities of black particles in road dust in Australia were particles of vehicle tires.

Figure 6 Microscopic image of microplastics from stormwater runoff.

Microplastic Removal Efficiency using Bioretention

The experiment of microplastic removal in lab-scaled bioretention was conducted using artificial microplastics made from tire wear to represent black fragment particles, which were the dominant type of microplastics identified in stormwater runoff from roads. A microscopic image of the artificial microplastic is shown in Figure 7. The concentration of microplastics in the inlet varied in the range of 73 to 974 particles/L. The result showed a reduction of the microplastics concentration at the outlet with a removal efficiency in the range of 92.4% to 99.3%. The average microplastic removal efficiency was 97.2%. As some microplastics still remained at the outlet, the term 'removal' in this study refers to the elimination of the microplastics from the stormwater runoff. The results of microplastic removal efficiency using bioretention for every variation are shown in Table 2.

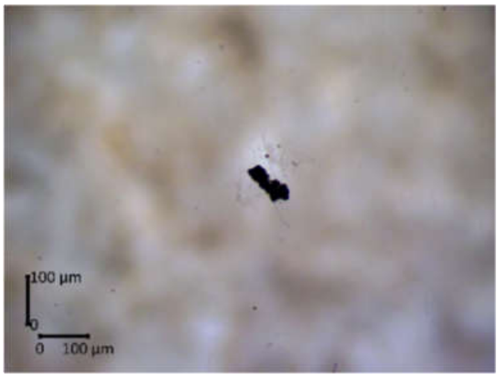

Figure 7 Microscopic image of artificial microplastic.

Table 2 Results of microplastic removal efficiency using bioretention for every variation.

Discharge	**Vegetation**		
	No Vegetation	*Vetivera*	*Hibiscus*
Low	98.3%	95.9%	96.3%
	92.4%	95.9%	94.4%
	97.5%	98.6%	99.3%
Moderate	96.7%	98.4%	96.8%
	95.7%	99.1%	98.1%
	97.6%	96.2%	98.6%
Hight	99.2%	99.3%	97.8%
	94.2%	94.0%	98.2%
	98.1%	98.9%	98.9%

Although the bioretention could not remove all microplastics, it was still effective in reducing microplastics in stormwater runoff from roads. The removal efficiency in this study was higher than in a field study in Canada, which showed a median of microplastic concentration reduction over two years of study of 84% [12]. A study in San Fransisco also showed lower removal of microplastics, which was 91% [6].

Microplastic Removal Based on Particle Size

The characteristics of microplastics in artificial water samples were divided into two categories based on their particle size, namely the size ranges of 25 to 125 µm and 126 to 4750 µm. The removal results showed that the bioretention column could remove 126 to 4750 µm sized microplastics up to 100%. Meanwhile, the highest removal efficiency for microplastics with a size of 25 to 125 µm reached 99.7%. The average microplastic removal for each size range is shown in Figure 8.

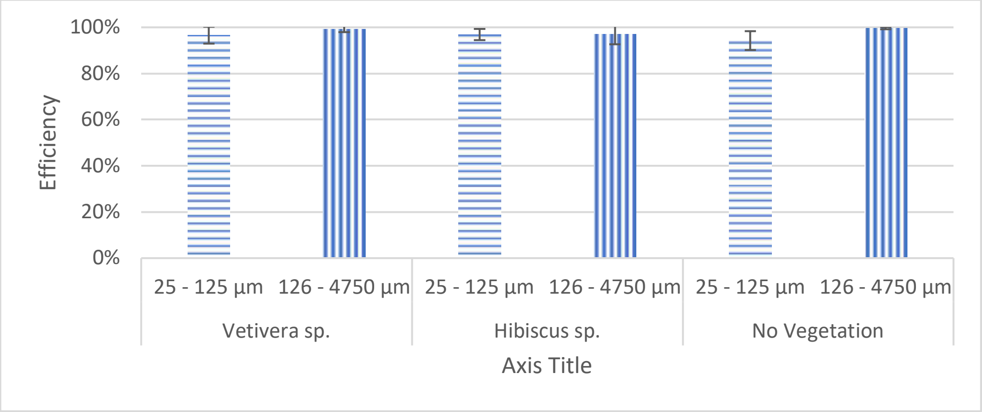

Figure 8 Microplastic removal efficiency based on particle size.

Figure 8 shows that the average removal efficiency of 126 to 4750 µm sized particles was higher than that of 25 to 125 µm sized particles. The results of statistical testing using the Mann-Whitney test (α = 5%) showed that there was an average difference in the removal efficiency of microplastics for sizes 25 to 125 µm and 126 to 4750 µm. The results were compared with the study from Gilbraeth *et al*. [18], where the trend of microplastic removal showed that the larger sizes of microplastics were easier to remove. The efficiency removal of > 500 µm, 355 to 500 µm, and 125 to 355 µm was 100%, 81%, and 55%. A similar result was shown in the study from Werbowski *et al*. [6], where the highest reduction was for 3.5 to 5 mm sized microplastics (largest size range) and the lowest efficiency was the removal of less than 0.5 mm sized microplastics (smallest size range). This could happen as microplastics larger than a large portion of the bioretention cell pore diameter should be removed by physical filtration [12].

Effect of Vegetation on Microplastic Removal

Variation of vegetation was done to examine the effect of vegetation on the removal of microplastics using a bioretention cell. The vegetations used in this study were *Vetivera* sp. and *Hibiscus* sp. The examination was also done on bioretention without vegetation as a control. The average removal efficiency of microplastics based on the presence of vegetation is shown in Figure 9.

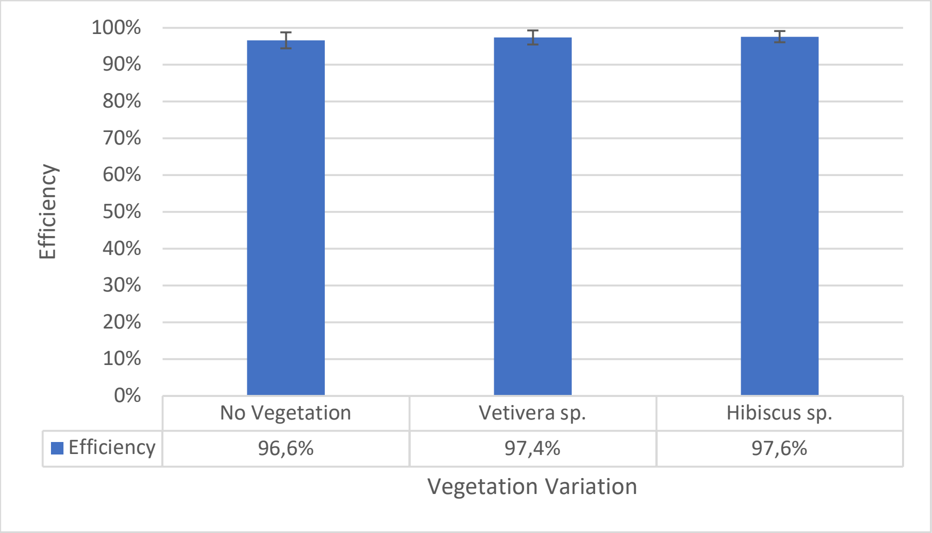

Figure 9 Average microplastic removal efficiency based on vegetation variation.

Figure 9 showed that the highest microplastic removal efficiency occurred in the bioretention with *Hibiscus* sp. Meanwhile, the lowest microplastic removal occurred in the control reactor without vegetation. The presence of vegetation with roots could form preferential pathways for water and associated substances so that microplastics would be concentrated along root channels as shown in the study by Kuoppamäki *et al.* [17]. The normality test, using Shapiro-Wilk (α = 5%), showed the data for bioretention without vegetation, with *Vetivera* sp. and *Hibiscus* sp. normally distributed, with significance values of 0.352, 0.098, and 0.285, respectively. The One Way ANOVA test (α = 5%) showed that the significance of each variation was higher than 5%, indicating that there was no significant difference in the average removal efficiency among the bioretention columns without vegetation, with *Vetivera* sp., and with *Hibiscus* sp. Therefore, the presence of vegetation did not have a significant effect on microplastic removal using bioretention. This result was compared with the study from Lange *et al*. reported in [13] that showed that the removal of 100 to 300 µm sized rubber and bitumen in a filter cell with vegetation and a filter cell without vegetation had no significant difference (Mann-Whitney test, Rubber: W = 59,5, p = 0.248; Bitumen: W = 62, p = 0.361). This indicates that the microplastic removal was mainly affected by other components of the bioretention system, which was most likely the filter media.

Effect of Discharge Variation on Microplastic Removal

The effect of discharge on microplastic removal using bioretention was examined by conducting variation of discharge based on rainfall intensity category, i.e., low rainfall (10 mm), moderate rainfall (35 mm), and heavy rainfall intensity (75 mm). The results of discharge calculation for each category were 4.5 ml/s, 15.6 ml/s, and 33.5 ml/s, respectively. The average efficiency for removing microplastics based on the flow rate is shown in Figure 10.

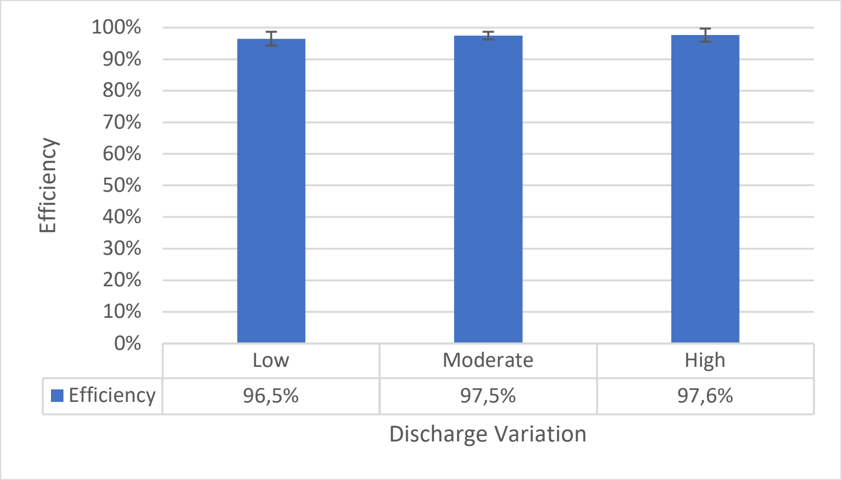

Figure 10 Average microplastic removal efficiency based on discharge.

Figure 10 showed that the highest microplastic removal efficiency was observed for the high discharge variation, while the lowest was for the low discharge variation. The Shapiro-Wilk normality test showed that the significance for low, moderate, and high discharge was 0.714, 0.696, and 0.005, respectively, indicating that the high discharge data were not normally distributed. The statistical test results using Kruskal-Wallis (α = 5%) showed that the significance of each variation was higher than 5%, indicating that there was no significant difference in the average removal efficiency using a bioretention column at low, medium, and high discharge variations.

The study from Davis *et al.* [4] showed that stormwater runoff volume and bioretention performance have a strong correlation, where low-discharge stormwater runoff could work more effectively. Lower discharge allows for more stormwater runoff to be intercepted and retained, causing an increase in soil-water contact. Longer soil-water contact will enhance sorption, precipitation formation, and biological uptake [5]. This condition may not be applied to microplastic removal as the physical filtration by straining does not need much reaction time as in biological and chemical processes. However, further study must be conducted to examine the possibility of leaching in bioretention with high discharge for a longer operating duration.

The Fate of Microplastic Removal in Bioretention Cells

The statistical analysis showed that vegetation had no significant effect on microplastic removal using bioretention. This proves that the main factor affecting the microplastic removal in bioretention is the filter medium. The mechanism of microplastic removal in a bioretention cell is straining, where the microplastic particles larger than the pore size in the media are trapped and removed [37]. The microplastic particles were observed at media depths of 10 cm, 30 cm, and 90 cm to obtain the distribution of microplastic removal in the bioretention cell based on particle size as shown in Figure 11.

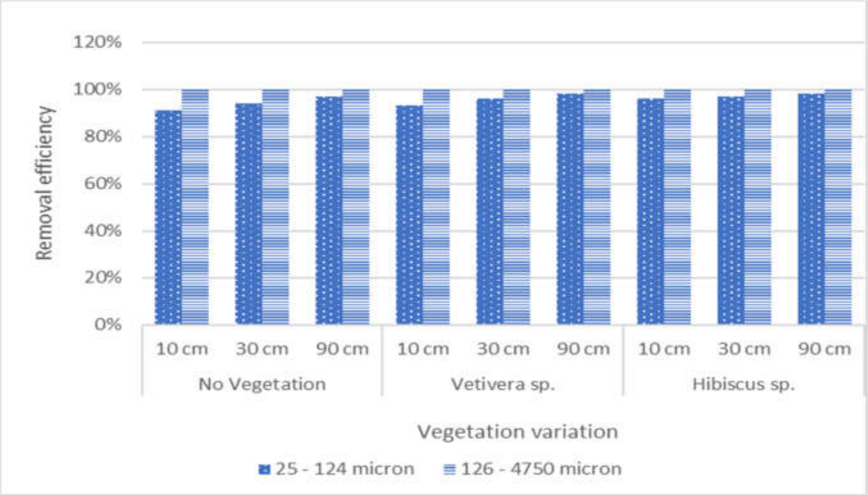

Figure 11 Distribution of microplastic removal in a bioretention cell based on particle size.

Figure 11 shows that the most significant reduction of microplastic particles occurred at a depth of 10 cm. The removal efficiency of 125 to 4750 µm sized microplastic at a media depth of 10 cm was 100%. The removal efficiency of 25 to 124 µm sized microplastics at a media depth of 10 cm only reached 96%, while further removal by the deeper media still occurred at a much lower reduction. This may have occurred because the microplastics that were larger than the pore size were already retained by the straining mechanism at a depth of 10 cm, so the reduction of microplastics by the deeper media would be lower.

Since microplastics are mainly removed through the straining mechanism, they accumulate over time in the filter media. This accumulation of microplastics, along with other suspended solids, can cause clogging, which affects the performance of the bioretention system. Clogged filter media can result in water overflow in the bioretention system, bypassing treatment and causing flooding. The roots of the vegetation in the bioretention system create macropores and root channels that enhance hydraulic conductivity and prevent filter media from clogging [38]. Further research is necessary to develop effective methods for managing microplastics clogging cdthe filter.

Kinetics of Microplastic Removal Using Bioretention

The removal kinetics of microplastics using bioretention was shown by the first-order removal constant of the plug flow reactor model. The results of the linear regression graph of the natural logarithmic microplastic concentration versus distance are shown in Table 3. The value of the 1st-order kinetic removal constant can indicate the rate of removal by filtration based on depth. The greater the k value, the greater the microplastic removal rate relative to the depth of the filter media.

Table 3 First-order removal kinetic constant.

Variation	R^2	k
No Vegetation	0,6058	0,0327
***Vetivera* sp.**	0,61	0,0356
***Hibiscus* sp.**	0,4492	0,034

These results show that bioretention with *Vetivera* sp. had a higher microplastic removal rate than *Hibiscus* sp. Meanwhile, bioretention without vegetation had the lowest microplastic removal rate. The higher rate of microplastic removal in bioretention with vegetation could be due to the retention of microplastics in the roots. *Vetivera* sp. has a type of fibrous root that tends to spread more near the soil surface of the media, while *Hibiscus* sp. has a taproot that tends to go deeper into the media. Therefore, more microplastics will be removed at greater depths using bioretention with *Hibiscus* sp. compared to *Vetivera* sp.

Conclusion

Bioretention cell was effective in removing microplastics from stormwater runoff from roads with a high efficiency in the range of 92.4% to 99.3% and an average efficiency of 97.2%. The normality test showed that the data for vegetation variation was normally distributed, while the data for discharge variaston was not normally distributed. Statistical analysis (α = 5%) showed that variations in vegetation and discharge had no significant effect on the efficiency of microplastic removal using bioretention. The microplastics were removed by a straining mechanism that significantly occurred at a media depth of 10 cm. First-order kinetic analysis showed that the kinetic removal constant of the bioretention with *Vetivera* sp., bioretention with *Hibiscus* sp., and bioretention without vegetation was 0.0356, 0.034, and 0.0327, respectively. The results indicated that bioretention with vegetation had a higher removal rate relative to the bioretention without vegetation. Therefore, more microplastics will be removed at greater depth using bioretention with *Hibiscus* sp. compared to *Vetivera* sp.

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