Environmental Science and Pollution Research (2019) 26:14904–14919
https://doi.org/10.1007/s11356-019-05041-0

REVIEW ARTICLE

# A review of bioretention components and nutrient removal under different climates—future directions for tropics

Hui Weng Goh[1] · Khe Sin Lem[1] · Nor Ariza Azizan[1] · Chun Kiat Chang[1] · Amin Talei[2] · Cheng Siang Leow[3] · Nor Azazi Zakaria[1]

Received: 21 January 2019 / Accepted: 29 March 2019 / Published online: 11 April 2019


## Abstract

Bioretention systems have been implemented as stormwater best management practices (BMPs) worldwide to treat non-point sources pollution. Due to insufficient research, the design guidelines for bioretention systems in tropical countries are modeled after those of temperate countries. However, climatic factors and stormwater runoff characteristics are the two key factors affecting the capacity of bioretention system. This paper reviews and compares the stormwater runoff characteristics, bioretention components, pollutant removal requirements, and applications of bioretention systems in temperate and tropical countries. Suggestions are given for bioretention components in the tropics, including elimination of mulch layer and submerged zone. More research is required to identify suitable additives for filter media, study tropical shrubs application while avoiding using grass and sedges, explore function of soil faunas, and adopt final discharged pollutants concentration (mg/L) on top of percentage removal (%) in bioretention design guidelines.

**Keywords** Best management practices · Bioretention · Filter media · Nutrient removal · Stormwater management · Tropical climate

## Introduction

Rapid development of land, including industrialization and urbanization, has changed the surface runoff characteristics by increasing the volume of stormwater runoff and the amount of pollutants flowing downstream to the receiving water. Understanding the problems of urbanization and further implementing mitigation steps on urban stormwater hydrology is critical in addressing the issues (Liu et al. 2014a).

Responsible editor: Philippe Garrigues

✉ Hui Weng Goh
ghw.red007@gmail.com

1 River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia, Engineering Campus, Nibong Tebal, Penang, Malaysia

2 Discipline of Civil Engineering, School of Engineering, Monash University Malaysia, 47500 Bandar Sunway, Selangor Darul Ehsan, Malaysia

3 Jacobs' Water Scotland team, Jacobs UK Ltd, Edinburgh, UK

Bioretention systems were developed in the 1990s by Prince George's County, Md. (PGC 2007) as one of the promising "at source" structural stormwater best management practices (BMPs). Basic components of a bioretention system are shown in (Fig. 1). The advantages of bioretention systems are the following: (1) providing water quality control by removing sediment loads, nutrients (Davis et al. 2006; Dietz 2007; Luell et al. 2011), heavy metals (Chapman and Horner 2010; Sun and Davis 2007), and pathogens (Zhang et al. 2011a; Hathaway et al. 2009) that exist in stormwater runoff, and (2) being able to reduce the stormwater peak flow and volume by infiltration and evapotranspiration (Roy-Poirier et al. 2010).

Extensive studies have been conducted on the performance of bioretention cells *to understand their function*, *improve their performance*, and *lengthen their lifespan* (Liu et al. 2014a) in temperate regions such as Australia, the USA, and New Zealand. Despite having successful studies that show effective removal of pollutants and reduction of runoff volume, the performance of bioretention system varies due to geological locations as different regions have different runoff characteristics, i.e., rainfall regimes, population density, and land use (Duncan 1999). However, the performance of

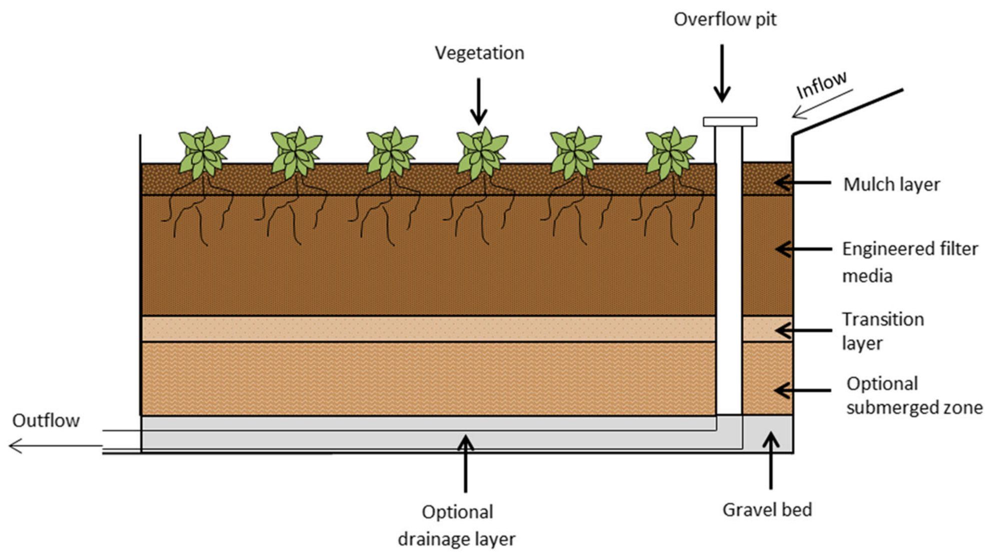


**Fig. 1** Components of bioretention systems, modified from Payne et al. (2015)

bioretention in regions where the climate differs significantly from temperate climates, especially the tropics is uncertain (Wang et al. 2017).

Although different countries should develop their own bioretention design criteria based on their local climate and runoff condition, the studies focused on utilizing bioretention systems in tropical countries are still at an early stage of development. As the bioretention design guidelines in tropical countries are modeled after those of temperate areas (Wang et al. 2017), substantial knowledge gaps exist in various areas. There are questions that need to be answered: (1) Can bioretention systems developed based on tropical design guidelines adopted from temperate countries perform effectively under tropical rainfall regime and pollutant compositions? (2) What is the performance and advancement of current bioretention designs in both tropical and temperate countries? (3) Are the recommended components (i.e., usage of mulch layer or submerged zone) and plants in these guidelines appropriate for tropical bioretention systems? (4) How should the current bioretention design guidelines be modified for tropical countries to suit their climates and the corresponding runoff characteristics?

To address these questions, this review paper: (1) compares the runoff characteristics and composition between temperate and tropical countries to discuss the suitability of adopting bioretention design guidelines from temperate countries for tropical countries; (2) summarizes the state of performance and advancement in published laboratory-scale and on-site bioretention studies; (3) discusses the application of some design recommendations on mulch layer, submerged zone, additives, plant selection, and macrofauna in tropical bioretention systems; (4) provides a greater refinement of bioretention components to encourage wider usage of this stormwater BMPs especially in tropical climate.

## Review of bioretention components and pollutant removal requirements under temperate and tropical climate

### Characteristics and composition of urban runoff

Rainfall patterns are mostly affected by factors such as geographical location, seasons, and climate change (Suhaila and Jemain 2012). In the tropics, frequent, short, and intense thunderstorms are the norm (Wang et al. 2017), which are less common in temperate climates. The average annual precipitation in temperate countries such as Australia, the UK, and the USA are below 800 mm, while in tropical countries such as Singapore and Malaysia are about 2500 mm (Goh et al. 2017). This is crucial to the design of bioretention systems especially in sizing consideration, as an undersized design might have insufficient storage capacity that may cause runoff to bypass the system (Wang et al. 2017). Therefore, for large countries such as Australia, the USA, and China, different stormwater BMPs guidelines have been used for different regions within these countries.

Bioretention basins designed for temperate countries are expected to capture the first flush of runoff which normally contains high concentration of pollutants. However, as rainfall tends to be intense and frequent in tropical climate, the first flush effect could be weak (Wang et al. 2017) while the urban runoff characteristics and nutrients concentration in tropical regions are also different from temperate regions. Duncan (1999) determined the typical nutrients composition of urban runoff based on the extensive review of 40 years of data for more than 60 cities worldwide, a summary of which is shown in (Table 1).

This review revealed that the concentration of total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) were, on average, highest in agricultural lands while concentration of total lead, biochemical oxygen demand ($BOD_5$), chemical oxygen demand (COD), total coliforms, fecal coliforms, and fecal streptococci were, on average, highest in high urban catchments. Stormwater runoff in a mix development catchment in the USA showed a wide range of TSS, TN, and TP concentrations (Hudak and Banks 2006) due to the higher concentration of TSS and pesticides in earlier storm while lower in later storm. In developing countries, such as Malaysia and China, high concentration of pollutants, particularly TSS (204 to 1110 mg/L), $BOD_5$ (58.3 to 112 mg/L), and COD (37 to 352 mg/L), as well as TP (0.9 to 8.2 mg/L), are reported (Chow and Yusop 2014; Luo et al. 2012). On the contrary, the concentration of TSS (36.5–54.4 mg/L), TN (1.36–1.57 mg/L), and TP (0.21–0.34 mg/L) in Australia is much lower (Lucke et al. 2018). Pollutants concentration of stormwater runoff, especially nutrients, is much higher in developing countries compared to developed countries. This could be attributed to the leaching from agricultural and farming activities, rapid urbanization, and industrialization that increase the impervious surfaces in developing countries. Therefore, the bioretention systems should be designed to perform at national and regional basis.

## Bioretention components requirement

In both tropical and temperate countries, stormwater BMP manuals employed specific guidance on the selection and sizing of bioretention systems according to the range of applications, configuration, drainage profile, and design themes. Urban runoff characteristics also vary between countries within the same climatic region due to the localized differences in soil properties, rainfall patterns, seasons, land use, and the level of development. The bioretention systems are widely applied in some developed countries with temperate climate, especially Australia and the USA, where various design guidelines have been developed according to their climatic patterns.

Two example guidelines from Australia and three from the USA, are shown in (Table 2) to compare their differences in terms of required design components and pollutant removal efficiency. China, as a developing country with temperate climate, has implemented the Sponge City Construction initiative (Jia et al. 2017) for which the Guide of Sponge City Construction Technology—low-impact development (LID) Technique (Trial) has been developed and used as the main guideline (MHURC 2014). There are also several other localized guidelines being implemented in China, including Wuhan sponge city design guideline (trial) and Suining sponge city design guideline (trial). Since China is in the early stage of implementing the Sponge City concept, the complete guidelines on bioretention design are yet to be finished. The bioretention classification in this guideline is relatively simpler compared to other temperate countries.

For tropical climates, majority of design guide mostly adopt design criteria from temperate region, regardless of economic status. As an example, for developed countries in tropics (Singapore), the Engineering Procedures for Active, Beautiful, Clean (ABC) Waters Design Guidelines is modeled after those of temperate areas (primarily Australia) such as Adoption Guidelines for Stormwater Biofiltration Systems, Australia (Wang et al. 2017). For developing countries in tropical climate, Urban Stormwater Management Manual for Malaysia (MSMA) adopted bioretention design guidelines of temperate countries, such as Maryland Stormwater Design Manual (MDE). This shows a lack of design criteria tailored to tropic regions.

**Table 1** Reported nutrient compositions of urban runoff in various countries

| Country | Source | Pollutant (mg/L) | | | | | Author |
|---|---|---|---|---|---|---|---|
| | | TSS | TN | TP | $BOD_5$ | COD | |
| Worldwide | Mixed residential, commercial, industrial catchment | 45 to 580 | 1.5 to 5.5 | 0.15 to 0.90 | 5.5 to 31 | 32 to 400 | Duncan (1999) |
| Malaysia | Mixed residential, commercial catchment | 411 ± 379 | N/A | 8.2 ± 2.8 | 58.3 ± 20.4 | 37.0 ± 29.5 | Ho and Tan (2013) |
| Malaysia | Mixed residential, commercial, industrial catchment | 204 ± 182 | 3.0 ± 1.2 | 0.9 ± 0.2 | 82.7 ± 75.0 | 222.3 ± 197.5 | Chow and Yusop (2014) |
| China | Storm sewer | 1110 ± 1560 | 6.1 ± 3.7 | 2.0 ± 1.5 | 112 ± 88 | 352 ± 207 | Luo et al. (2012) |
| United States of America | Mixed development catchment | 45 to 982 | 0.1 to 8.0 | 0.36 to 2.46 | N/A | N/A | Hudak and Banks (2006) |
| Australia | Urban residential | 54.4 ± 73.9 | 1.57 ± 1.74 | 0.34 ± 0.73 | N/A | N/A | Lucke et al. (2018) |
| Australia | Commercial | 36.5 ± 41.95 | 1.36 ± 1.08 | 0.21 ± 0.29 | N/A | N/A | Lucke et al. (2018) |

*N/A*, not available

**Table 2** Classifications of bioretention system according to the selected BMP Manuals

| BMP manuals | Category | Depth (m) | Soil compositions | $k_s$ (mm/h) | Nutrient removal requirement | | | Plant selection guide |
|---|---|---|---|---|---|---|---|---|
| | | | | | TSS | TN | TP | |
| Water by Design Bioretention Technical Design Guidelines | Temperate/developed | 0.5 to 1.0 | 100% sand and loam mix | 100 to 300 | 80% | 45% | 60% | Yes |
| Adoption Guidelines for Stormwater Biofiltration Systems, Australia | Temperate/developed | Min 0.5 | < 3% clay and silt<br>< 3% fine gravel<br>5 to 30% very fine sand<br>10 to 30% fine sand<br>40 to 60% coarse sand<br>0 to 10% very coarse sand | 100 to 300 | > 90% | > 50% | > 65% | Yes |
| Prince George's County (PGC) Bioretention Manual, USA | Temperate/developed | 0.75 to 1.2 | 20 to 30% top soil<br>50 to 60% sand<br>20 to 30% leaf compost | Min 25 | 97% | 33–66% | 35–65% | Yes |
| New Jersey Stormwater BMP Manual, USA | Temperate/developed | 0.45 to 0.6 | 85 to 95% sand<br>2 to 5% clay<br>3 to 7% organics | Max 250 | 90% | 30% | 60% | Yes |
| Pennsylvania Stormwater BMP Manual, USA | Temperate/developed | Min 0.45 | 20 to 30% compost<br>70 to 80% soil base | Not specified | 85% | 30% (nitrate) | 85% | Yes |
| Guide of Sponge City Construction Technology—LID Technique (Trial), China | Temperate/developing | 0.25 to 1.2 | 100% planting soil | Not specified | 75–90% | Not included | Not included | No |
| Urban Stormwater Management Manual (MSMA), Malaysia | Tropic/developing | 0.45 to 1.0 | 20 to 25% top soil<br>50 to 60% medium sand<br>12 to 20% leaf compost | 13 to 200 | 80% | 50% | 50% | Yes |
| Active, Beautiful, Clean (ABC) Waters Design Guidelines, Singapore | Tropic/developed | 0.4 to 0.6 | 100% sandy loam | 50 to 200 | 80% or less than 10 mg/L | 45% or less than 1.2 mg/L | 45% or less than 0.08 mg/L | No |

## Filter media composition

The main purpose of filter media is to filter and/or retain pollutants and to provide water and nutrients for vegetation. Sand and sandy loam are generally used as filter media in bioretention systems, due to their adequate hydraulic conductivity, low nutrients content, and structural stability. Payne et al. (2014) suggested using sand with different particles size (between 0.05 and 3.4 mm) to establish a stable media that provides sufficient infiltration rate and ensures enough water holding capacity to support plants' growth.

Different recommendations are given for filter media composition by different design manuals. Some guidelines recommend homogenous type of soil, while other manuals recommend mixture of different soil types. Water By Design (2014) recommends 100% sand and loam mix while PUB (2014) that follows the Australia guidelines also recommends 100% sandy loam. However, Davis et al. (2009) highlighted that the use of loam, which has low infiltration rate, may lead to failure of the system due to its high clay content (more than 30% by volume). Considering the lower average annual rainfall in Australia, the loam-based filter media may be accepted but this may not be suitable for application in Singapore, due to the much higher rainfall intensity. In China, the guidelines for bioretention suggests the soil composition of 100% planting soil, which may lead to high amount of nutrients leaching and lower hydraulic conductivity (MHURC 2014). As the China guidelines are still in the developing stage, the recommendations for filter media are yet to be finalized.

The three USA stormwater BMPs manuals recommended different soil compositions for bioretention design in different regions to ensure the consistency between County Soil Survey Data and soil test result at different location (NJDEP 2016). Stormwater BMPs manuals for Malaysia and the USA have more specific requirements on filter media as it is divided into different compositions including topsoil, sand, and organics (leaf compost). Sand provides highly saturated hydraulic conductivity, soft clay in the topsoil provides high pollutant removal especially heavy metals, and organics (compost) helps to sustain vegetation. Thus, the combination of filter media provides optimum performance of bioretention. Although Malaysia guideline for bioretention soil composition is similar to the one provided in PGC manual, lower leaf compost percentage is recommended in Malaysia guideline to prevent nutrients leaching (DID 2012).

## Filter media depth

The filter media is the central component of bioretention systems that controls the flow and determines the water quality of the effluent. The depth of filter media will affect the runoff storage volume of the system and pollutants removal (Brown and Hunt III 2010). The recommended soil media depth by several BMPs manuals ranges between 0.4 and 1.0 m according to the plant selection, are given in (Table 2). Shallower soil media is to be used with herbaceous plant species while deeper soil media is to be used for woody shrubs or trees. PGC (2007) suggests a higher depth of filter media, from 0.75 to 1.20 m, following the recommendation in Maryland stormwater design manual (MDE 2000). Bioretention manual in China recommends a wider range of filter media depth varies from 0.25 to 1.20 m as it serves as a general guideline across the country.

## Hydraulic conductivity

Saturated hydraulic conductivity ($k_s$) is another parameter besides filter media depth that affects the capacity and pollutant removal performance of a bioretention systems, as it influences the capability of a bioretention filter media to achieve the ponding draw down time (surface infiltration rate). The purpose of draw down duration is to allow sufficient contact time for pollutants removal. The recommended $k_s$ values in stormwater BMPs manuals varies across a wide range (Table 2) due to the consideration that different pollutants will be removed at different targeted infiltration rates. For example, as rainfall intensity in tropical countries is normally higher than temperate countries, a higher $k_s$ requirement is expected to optimize the amount of runoff flowing through the bioretention media. However, lower $k_s$ will cause longer retention time, thus enabling more reaction time between soil microbes and pollutants and the removal efficiency will be increased.

Studies have been conducted to determine the most appropriate $k_s$ to maximize the amount of runoff treated by optimizing the contact time of runoff with filter media so that the quality of treated runoff will not be compromised. According to LeFevre et al. (2014), a bioretention system should infiltrate water at a minimum rate of 20 mm/h. Hunt and Lord (2006) recommended a targeted infiltration rate of 25.4–50.8 mm/h for TN, 50.8 mm/h for TP, and 50.8–152.4 mm/h for TSS, metals, and pathogens. Hsieh et al. (2007a) reported the usage of a high-conductivity media layer over a low-conductivity media layer to increase contact time for removal of dissolved phosphorus. Study of Lucas and Greenway (2011) revealed an increase in nitrogen removal with an extended hydraulic residence time in the system. To date, most studies on bioretention hydraulic conductivity were conducted for temperate climates. Hence, more research is required to obtain the optimum hydraulic conductivity to suit tropical climate.

## Plant selection

Bioretention design guidelines recognize the functional effect of vegetation in the performance of bioretention systems.

Plants are particularly critical in uptake of nutrients, maintaining infiltration capacity of bioretention, and also provide additional benefits of enhancing biodiversity, creating microclimate, and improving aesthetical value (Payne et al. 2015).

Various guidelines with detail plants selection have been established and developed in temperate countries such as the USA and Australia which provide detail information on plant characteristics, planting method, and the capability of nutrients removal (NJDEP 2009; PGC 2007; Water By Design 2014). PGC (2007) provides requirements for plant growth in bioretention, including light, soil moisture, and drought tolerance. Besides, plants characteristic, such as blooming time, mature size, and wildlife value are also provided. Water By Design (2014) outlines the core and supplementary vegetation species, planting density, and minimum number of plant species that are suitable to be planted in certain regions (wet tropics, dry tropics, subtropics, arid zones). NJDEP (2016) provides planting methods (seeds, bare-root, or plants) and inundation tolerance of plants. Moreover, DEP (2006) mentions about wildlife value, light requirement, and inundation and drought tolerance of vegetation.

On the other hand, stormwater BMPs guideline in tropical countries, for example, Malaysia, only provides a list of native plants (DID 2012), whereas Singapore's and China's guidelines do not include plants selection guides. It was stated that the National Parks Board of Singapore should be consulted in determining suitable plantings for bioretention basins in Singapore (PUB 2011). To date, there has been a lack of detailed information on planting method and nutrients removal capability in these guidelines used in the tropics. Therefore, a comprehensive guideline on the plants' selection for bioretention system needs to be developed in which details such as vegetation planting methods, growth characteristics and requirements, ecological value, and pollutants uptake capability according to tropical climate condition should be included.

## Pollutant removal requirements

The importance of nutrients removal from urban runoff has been emphasized in stormwater BMP manuals. PUB (2011) has listed TSS, nutrients, $BOD_5$, COD, and pathogens as the pollutants that contribute the most significant impacts on Singapore's ecology, whereas the Malaysia Environmental Quality Report (DOE 2012) stated that the major pollutants detected from rivers in Malaysia are $BOD_5$, ammoniacal nitrogen ($NH_3$-N), and TSS. However, in most of the stormwater BMP manuals, only three water quality parameters: TSS, TN, and TP, are considered for performance assessment of bioretention basins. According to various stormwater BMPs manuals Table 2, bioretention basins are generally designed for removal rates of 75–97% for TSS, 30–66% for TN, and 35–85% for TP. These design requirements are guidelines for further research in enhancing the performance of the current bioretention design.

Although most of the guidelines around the world provide recommendations for pollutants removal percentage, Singapore's guideline includes maximum pollutants concentration (mg/L) in the effluent as the design criteria. The inclusion of recommended pollutants concentration in the effluent is beneficial as relying on percentage removal as the only reported performance measure can generate misleading conclusions on bioretention performance (Davis et al. 2009). For example, influent with high concentration may result in higher removal. On the other hand, when the runoff concentration is relatively low, the effluent discharges may not have much difference from the influent. In this case, the percent removal (%) will be low, but the discharged water is of good quality. Therefore, it is suggested for bioretention design guidelines to provide recommended final discharged pollutants concentration (mg/L) on top of removal percentage.

## Review of bioretention systems performance

Since the introduction of bioretention in the 1990s (PGC 2007), various researches have been conducted to improve bioretention performance and create cost-effective bioretention design under different climate conditions. This section will discuss on general nutrient removal performance of bioretention, and also the performance of bioretention categorized under three classes: filter media, plants, and components.

### General TSS, TN, and TP removal performance

TSS comprises a variety of solid particles (organic and inorganic matters) such as silt, decaying plants fallen leaves, and wastes that are suspended in runoff water. TSS can be captured via settling and filtration while they will be further removed effectively through a sedimentation process in the basin (Davis 2007; LeFevre et al. 2014; Liu et al. 2014a). High concentration of TSS can impair water quality and cause clogging in the conveyance system of the bioretention (Roy-Poirier et al. 2010). Generally, TSS removal was high in bioretention systems, and the removal performance was not affected greatly by bioretention components such as filter media type and vegetation. Studies conducted using different filter media, including concrete and masonry sand (Barrett et al. 2013); vegetated skype sand and loamy sand (Glaister et al. 2014); and fine sand, sandy loam, mixture of sandy loam with mulch, charcoal, perlite, or compost (Hatt et al. 2008) showed TSS removal in the range of 88 to 99%. Barrett et al. (2013) revealed that TSS removal is not significantly affected by vegetation, where bioretention with plants achieved TSS removal of 90 to 96%, and without plants (91 to 95%). Comparison of (Tables 3 and 4) shows that the general removal performance of TSS in laboratory studies (85% to more than 90%) was better than on-site studies (53% to more than 90%). Although most of the bioretention studies show positive TSS removal, there are some exceptions where the system may even leach TSS (Hunt et al. 2006). Moreover, in bioretention studies, TP removal is mainly correlated with TSS removal. This is evident in studies by Hunt et al. (2006) and Glaister et al. (2014) where TP removal is associated with TSS removal. It is worth mentioning that TN removal in bioretention systems is generally linked to the formation of an anaerobic zone in the soil mass, which promotes denitrification in the system (Dietz and Clausen 2006), indicated that TN removal in bioretention was not associated with TSS and TP in the soil.

TP removal is through filtration, adsorption, and microbial action (Davis et al. 2006). Factors affecting TP removal include existence of plants, types of filter media, and soil conductivity. Lucas and Greenway (2008) laboratory scale study found that the TP retention in vegetated loam was 92% while non-vegetated loam was 56%. Besides, TP retention in loam, sand, and gravel were 56%, 39%, and 14%, respectively, which showed that TP retention was affected by different filter media and vegetation (Lucas and Greenway 2008). In another study, high conductivity filtration media was found capable of retaining more TP when compared with low conductivity filter media. This was evident as the TP retention for high conductivity filter media was 85% compared to 65% for low conductivity (Hsieh et al. 2007a).

TP removal performance is effective in both laboratory and site studies Tables 3 and 4 with general removal rate of 65 to 97%. A study by Hsieh and Davis (2005) reported wide range of TP removal, due to the chemical properties of filter media and flow behaviors of runoff through the media. Blecken et al. (2007) revealed that phosphorus can be removed well in cold temperature (2 and 8 °C). Hunt et al. (2006) found an increase of TP (65 to 240%) in the effluent of bioretention site due to the use of high phosphorus index (86 to 100) soil.

The performance of TN removal is in wide range from only 1% (Hsieh and Davis 2005) to 99% (Milandri et al. 2012). Factors affecting TN removal include existence of plants, types of filter media, and hydraulic retention time (HRT). Nitrogen removal could be increased with plants through the roots' uptake (Henderson 2009). Moreover, study of Lucas and Greenway (2008) resulted in TN removal of 76% in vegetated loam while only 18% removal was achieved in non-vegetated loam. Besides, filter media could affect TN removal. Lucas and Greenway (2008) conducted mesocosm study using "Wheelie-bin" and achieved 76% TN removal in vegetated loam while only 40% removal happened in vegetated gravel. Column study by Hatt et al. (2008) revealed that sand as filter media gives better TN removal rate of 38% while the use of sandy loam and mixture of sandy loam caused 18 to 164% increase in TN concentration in the effluent. Hatt et al. (2008) suggested that the large nutrients leaching was due to the outflow of native materials rather than failure of the system in retaining the pollutants. Unlike the high TN leaching problem in the Hatt et al. (2008) study, the greenhouse mesocosm study by Goh et al. (2017) showed promising TN removal, with 52.2% as the bioretention was allocated adequate period for mesocosm establishment.

HRT has strong influence on denitrification (POP et al. 2013). A study conducted by Brown and Hunt (2011) revealed that HRT less than 3 h can be effective for stormwater volume reduction but ineffective for nitrogen removal. Blecken et al. (2007) conducted a study on the effect of temperature and found that nitrogen cannot be reduced under low temperature (2 and 8 °C) because there are insufficient denitrification and high leaching from the column. The astounding TN leaching in laboratory study has been reported by Bratieres et al. (2008) and Blecken et al. (2007) with the leaching of 208 and 241%, respectively, while Brown and Hunt III (2010) found TN leaching of 75% at a field study which was attributed to the potential export of nitrate from the used fertilizer.

HRT has strong influence on denitrification (POP et al. 2013). A study conducted by Brown and Hunt (2011) revealed that HRT less than 3 h can be effective for stormwater volume reduction but ineffective for nitrogen removal. Blecken et al. (2007) conducted a study on the effect of temperature and found that nitrogen cannot be reduced under low temperature (2 °C and 8 °C) because there are insufficient denitrification and high leaching from the column. The astounding TN leaching in laboratory study has been reported by Bratieres et al. (2008) and Blecken et al. (2007) with the leaching of 208% and 241%, respectively, while Brown and Hunt III (2010) found TN leaching of 75% at a field study which was attributed to the potential export of nitrate from the used fertilizer.

## Filter media

This section will discuss on the performance of filter media in bioretention, which are mulch layer, additives, and soil macrofauna.

### Performance with mulch layer

Various bioretention basin design guidelines suggested a mulch layer above an engineered soil layer (DEP 2006; DID 2012; MHURC 2014; NJDEP 2016; PGC 2007; PUB 2014; Water By Design 2014). The main function of the mulch layer is to keep the soil moisture, aid plants growth, suppress weeds, and protect underlying soil from drying and eroding (Trowsdale and Simcock 2011). Mulch layer is also found to be able to act as a filter for certain pollutants. Hsieh et al. (2007b) explained that mulch layer can enhance nitrification process, as higher organic content from mulch with a

**Table 3** Reported pollutants removal performance of bioretention at site studies

| Name of site | Pollutant load reduction (%) | | | Use of additives | Use of submerged zone | Author |
|---|---|---|---|---|---|---|
| | TSS | TN | TP | | | |
| University of Maryland, College Park, MD, USA | 96.4 | 41 | 55.1 | WTR* | No | Liu and Davis (2013) Li and Davis (2014) |
| Lenexa, Kansas, USA | 90 | 56 | N/A | Wood mulch | No | Chen et al. (2013) |
| Nashville, NC, USA | 60 to 71 | − 75 to − 21 | − 2 to 19 | N/A | No | Brown and Hunt III (2010) |
| Lawrence Technological University in Southfield, MI, USA | 79.3 to 97.9 | 19.9 to 90.8 | 76.9 to 97.2 | N/A | No | Carpenter and Hallam (2009) |
| Charlotte, NC, USA | 59.5 | 32.2 | 31.4 | N/A | No | Hunt et al. (2008) |
| University of Maryland, College Park, MD, USA | 54 to 59 | 90 to 95 | 77 to 79 | Mulch/newspaper | No | Davis (2007) |
| Largo and Greenbelt, MD, USA | N/A | 49 to 59 | 65 to 87 | Mulch | No | Davis et al. (2006) |
| Greensboro, NC, USA | − 170 | 40 | − 65 to-240 | N/A | No | Hunt et al. (2006) |
| "Coomera Waters" residential estate, Gold Coast, Australia | 61.81–80.78 | 38.70–47.93 | 36.42–75.33 | N/A | No | Mangangka et al. (2015) |
| McDowall, Australia | 93 | 37 | 86 | N/A | No | Hatt et al. (2009) |
| Kongju National University, Chungnamdo, South Korea | 94.1 | 58.6 | 74.1 | N/A | No | Geronimo et al. (2013) |
| Balam Estate Rain Garden, Singapore | 53 | 25 | 46 | N/A | No | Wang et al. (2017) |

*N/A*, not available; *WTR*, water treatment residue

corresponding greater cation exchange capacity can promote ammonium adsorption. Jang et al. (2005) found that hardwood bark mulch has the best physicochemical properties for adsorption of heavy metals while Hsieh et al. (2007a) reported that mulch layer could prevent clogging after repetitive TSS input. In addition, the use of mulch layer may result in a media with less uniform and smaller grain size which can enhance the capability of capturing smaller particles (LeFevre et al. 2014).

Although there are substantial benefits reported from various researches in temperate countries, the appropriateness of mulch layer for bioretention design in the tropical climate is questionable. Bratieres et al. (2008) and Paus et al. (2014) reported that organic matter such as mulch used in bioretention practices can increase the phosphorus concentration in the infiltrating water as the organic matter decomposes and releases both organic and inorganic phosphorus. Davis et al. (2009) suggested that mulch layer may require a periodic replacement or removal. Consideration should be given to the application of mulch layer due to the problem of scouring and flotation of mulch during storm events as mulch is subjected to wash off from the site (NJDEP 2016; PGC 2007). In laboratory studies conducted by Palmer et al. (2013) and Goh et al. (2017), the mulch layer was excluded; however, the performance of bioretention system was still promising.

Considering the fact that the main function of mulch layer in bioretention systems is protecting the underlying filter media and helping plants' growth, the use of mulch layer in tropics may not be necessary due to the high rainfall condition. Tropics have enough rainfall to keep the soil wet and support plant growth. In addition, tropics do not have prolonged dry season that inhibits plant growth or extremely cold weather that causes soil freezing. Furthermore, tropics often receive a large amount of stormwater in a short period, which may cause scouring and flotation of mulch that can lead to an increase in nutrients leaching.

## Performance with additives

Additives were tested in bioretention systems as one of the approaches to enhance nutrients removal. Although in standard bioretention design, removal of TSS and TP are relatively better than TN removal performance, additives have been applied to further enhance the P removal. In some studies, water treatment residual (WTR) has been used as an additive in bioretention system in which aluminum-based WTR is suggested as amendments in bioretention soil media for better phosphorus removal (Palmer et al. 2013). O'Neill and Davis (2011) also used aluminum-based WTR as bioretention soil media amendments, and the result showed an applied-P mass reduction of 88.5% compared to an increase of 71.2% in P mass in effluent water when system was without the amendments. Goh et al. (2017) tested several additives and found cockle shells the most suitable additives for TP removal (percentage removal = 95.2%).

**Table 4** Reported pollutant removal performance of bioretention laboratory studies

| Temperate country | Scale of laboratory study | Pollutant load reduction (%) | | | Type of additives | Depth of submerged zone | Use of plant | Author |
|---|---|---|---|---|---|---|---|---|
| | | TSS | TN | TP | | | | |
| USA | 18nos × 10.2 cm dia. × 25 cm depth (large), 6nos × 5.1 cm dia. × 12.5 cm dia. (small) PVC | N/A | − 7.8 to 0 | − 16.7 to 0 | Biochar | N/A | No | Iqbal et al. (2015) |
| USA | 18nos × 56 cm dia. × 92 cm depth plastic storage drums | N/A | 7.5 to 67.6 | > 95 | WTR* | N/A | Yes | Liu et al. (2014b) |
| USA | 12nos × 200 mm dia. × 460 mm depth PVC | 88 to 97 | 59 to 79 | 77 to 94 | Shredded hardwood bark mulch | 150 mm | Yes | Barrett et al. (2013) |
| USA | 8nos × 226 cm × 36 cm × 56–65 cm depth (416-L polyethylene tank) | N/A | 7 to 75 | N/A | Woodchip | 300 mm | No | Gilchrist et al. (2013) |
| USA | 12nos × 365 mm dia. × 600–900 mm depth PVC | N/A | 33 to 71 | 61 to 80 | WTR* | 300 mm | Yes | Palmer et al. (2013) |
| USA | 2nos × 189 mm dia. × 900 mm depth columns | N/A | 36.4 | 88.5 | WTR* | N/A | Yes | O'Neill and Davis (2011) |
| USA | 30nos × 57 cm × 49 cm × 80 cm depth "wheelie-bin" containers | N/A | 40 to 76 | 44 to 92 | WTR* | N/A | Yes | Lucas and Greenway (2011) |
| USA | 107 cm × 76 cm × 61 cm depth (small box); 305 cm × 152 cm × 91 cm depth (large box) | N/A | 13 to 60 | 81 | N/A | N/A | Yes | Davis et al. (2006) |
| USA | 18nos × 191 mm dia. × 110 mm depth Plexiglas | 29 to 96 | 1 to 43 | 4 to 85 | N/A | N/A | No | Hsieh and Davis (2005) |
| USA | 12nos × 64 mm dia. × 400 mm depth Plexiglas | N/A | 70–80 | N/A | Newspaper | N/A | No | Kim et al. (2003) |
| USA | 15nos × 700 mm depth columns | N/A | 60–62 | N/A | Woodchip | N/A | No | Peterson (2015) |
| Australia | 20nos × 150 mm dia. × 600 mm depth PVC | 86 to 99 | 89 | 93 | Skye sand | 300 mm | Yes | Glaister et al. (2014) |
| Australia | 240nos × 150 mm dia. × 600 mm depth PVC | N/A | 58 to 93 | N/A | Pine chips | 300 mm | Yes | Payne et al. (2014) |
| Australia | 15 × 375 mm dia. × 900 mm depth PVC | 95 | 46 to 65 | 50 to 60 | N/A | 450 mm | Yes | Zinger et al. (2013) |
| Australia | 35nos × 300 mm dia. × 800 mm depth PVC | N/A | 93 | 93 | Jarrah woodchips | 300 mm | Yes | Zhang et al. (2011a, b) |
| Australia | 125nos × 375 mm dia. × 300–700 mm depth PVC | 95 to 99 | − 241 to 79 | 77 to 95 | N/A | N/A | Yes | Bratieres et al. (2008) |
| Australia | 6nos × 100 mm dia. × 800 mm depth PVC | 90 to 99 | − 164 to 38 | − 437 to 97 | N/A | N/A | No | Hatt et al. (2008) |
| Australia | 21nos × 150 mm dia. × 500 mm depth PVC | 98 | − 66 | 69 | N/A | N/A | Yes | Read et al. (2008) |
| Australia | 15nos × 377 mm dia. × 800 mm depth PVC | 97 | − 208 | 80 | N/A | N/A | Yes | Blecken et al. (2007) |
| Korea | Surface area $0.475 m^2$, total vol. $0.19 m^3$ (box A); Surface area $0.6 m^2$, total vol. $0.36 m^3$ (box B) | N/A | 49 to 55 | 85 to 86 | N/A | N/A | Yes | Geronimo et al. (2013) |
| Malaysia | 24nos × 300 mm dia. × 600 mm depth PVC | 85.4 to 98.4 | 52.2 to 80.4 | 84.9 to 92.7 | Newspaper and cockle shell | N/A | Yes | Goh et al. (2017) |
| Singapore | 7nos × 34 mm dia. × 300 mm depth columns | 93.4 | 59.8 | 92.7 | WTR* | N/A | No | Guo et al. (2014) |

*N/A*, not available; *WTR*, water treatment residue

In order to overcome poor TN removal and N leaching problem, researches have been conducted to find possible effective additive to be used. Additives such as shredded newspaper (Goh et al. 2017), shredded hardwood bark mulch (Barrett et al. 2013), woodchips (Peterson 2015; Gilchrist et al. 2013; Payne et al. 2014; Zhang et al. 2011b), and Skye sand (Glaister et al. 2014) have been used in bioretention system where reduction of nitrate leaching, as well as higher removal of TN (ranging from 59% to more than 90%), have been reported. Kim et al. (2003) was the first researcher that utilized additives to perform column studies. The study found that newspaper was the best additive for denitrification (with TN removal up to 80%), out of various additives tested (alfalfa, leaf mulch, compost, sawdust, wheat straw, wood chips, and elemental sulfur). The same finding is also reported by Goh et al. (2017) that found significant improvement in TN removal (80.4%) by using shredded newspaper.

Besides removal of TN and TP, Stander and Borst (2009) found addition of shredded newspaper layer in bioretention media can reduce the volume of urban runoff, with suggestion that newspaper layer may absorb stormwater. There is a recent study by Hermawan et al. (2018) in Malaysia that found halloysite nanotube achieved both high heavy metal ions removal and high infiltration rate. Despite of the promising performance of additives in treating stormwater runoff as mentioned, there are several essential factors to be considered to choose a suitable additive, including the targeted pollutants to be removed, long-term effect on the overall performance of bioretention, availability of the additives, and cost.

For application in tropics, additives that enhance denitrification in tropics are suggested as an alternative for submerged zone to ensure the effectiveness of bioretention system, especially in removing nitrogen. Although newspaper is proven to increase nitrogen removal in bioretention system in both temperate and tropical (Goh et al. 2017; Kim et al. 2003), newspapers are slowly phasing out due to paperless era. Besides newspaper, there were a few researches that have been carried out for other purposes. For example, Hermawan et al. (2018) used synthesized stormwater in lab-scale soil columns to identify proper soil filter media that can remove heavy metal ions efficiently, and Guo et al. (2014) suggested that coconut fiber could also potentially be used as an alternative organic source for filter media. Additional research is still needed to provide qualitative and quantitative design, and performance information in order to recommend the most suitable additives composition in filter media. Promising additives in bioretention systems for nutrients removal as discussed (shredded hardwood bark, woodchips, skye sand, and water treatment residuals) that have been tested in bioretention system in temperate countries could also be tested in the tropics.

## Performance with macrofauna

Soil invertebrates, also known as soil macrofauna, may play an important role in nutrients retention and/or removal in bioretention systems. A study of street-scale bioretention basin in Washington, DC, USA, revealed that the most common soil-dwelling taxa are earthworms, potworms, springtails, mites, fly larvae, adult and larval beetles, millipedes, centipede, isopods, ants, spiders, and snails (Ayers 2009), with earthworms recognized as major ecosystem engineers (Meysman et al. 2006). Leaves litter (Kazemi et al. 2009) and soil pH (Kappes et al. 2006) are the two main factors affecting soil fauna abundance and diversity. Considering the geographical and climatic factors, the studies of soil macrofauna vary spatially.

Soil macrofauna could affect the performance of bioretention by affecting infiltration rate, pollutants retention and/or removal, and plant growth. The burrowing activity of earthworm, millipedes, scarab beetles, spiders, bee, and wasps (Colloff et al. 2010) facilitate water and gas transport, improve infiltration, enhance drainage, and reduce clogging, hence further possessed the ability to delay the time before maintenance is needed (Mehring and Levin 2015, Shipitalo and Le Bayon 2004). Adugna et al. (2015) found that earthworms could extend the lifespan of filters as the experimental result of the unit without earthworm started to clog after 4 months while the unit with earthworm started to clog after 10 months. Conversely, the study of Jouquet et al. (2012) found that earthworm burrowing activity caused leaching of nitrate.

Despite the burrowing activities that may prevent clogging of filter media, casting activities of soil macrofauna could play an important role in affecting soil function especially in N removal. Taylor et al. (2003) found that more ammonium can be removed in the soil column with earthworm due to the production of earthworm casts. Earthworm cast can oxygenate the influent and assist in nitrification of ammonium. Although the soil condition is aerobic, anoxic condition in earthworm gut could facilitate the production of dinitrogen and nitrous oxide through denitrification (Horn et al. 2006), thus enhance nitrogen removal.

Studies by Chapuis-Lardy et al. (2011) and Wurst et al. (2003) found that earthworms enhance mobility and availability of nutrients to plants and stimulate plants growth. Bioturbation by earthworm can also enhance the expansion of roots and increase roots' density (Wurst et al. 2003). The enhancement of plant growth may indirectly improve the runoff effluent quality, as plants are able to uptake more nutrients from the runoff. However, the enhancement of nutrients mobility may also lead to an increase in leaching of nutrients (Suárez et al. 2004). The degree to which the effects of soil faunas counteract each other has not been explored yet but there are clear possibilities that the presence of soil fauna in bioretention system will change laboratory-based estimates of bioretention system performance in the field (Mehring and Levin 2015).

Soil macrofauna may alter the function of bioretention system in stormwater management, thus incorporating soil macrofauna in the studies of bioretention system may help manager and researches to understand, optimize, and predict longevity of bioretention systems (Mehring and Levin 2015). To date, there is lack of research on bioretention soil macrofauna in tropical countries. Tropical land has the highest density of soil fauna (González and Seastedt 2001), indicating that tropical land serves a favorable habitat for variety of soil faunas. As soil is readily inhabited by a wide array of soil fauna, the studies of the influence of soil macrofauna in bioretention system are crucial to understand and improve bioretention system in managing stormwater runoff. Therefore, future research on tropical bioretention systems should be focused on the distribution and composition of soil macrofauna through running controlled experiments that can assess the influence of soil macrofauna on the performance of bioretention systems.

## Performance of plants

Generally, the main criteria for selection of plant species for bioretention design are suitability for the local landscape and ecology, ability to survive under extreme conditions, and capability of rapid but not invasive establishment (Hunt et al. 2015). The appropriate type of plants and species should be chosen based on their effectiveness in removing the pollutants (Muerdter et al. 2018).

Barrett et al. (2013) revealed that columns with vegetation showed improvement in nutrients removal (59–79% of TN and 77–94% of TP), while columns without vegetation were found to export substantial amount of nitrate/nitrite. Root depth is an important factor in determining the effectiveness of nitrogen removal. In a study conducted in Texas, Big Muhly grass (*Muhlenbergia lindheimeri*) with root depth of ~ 460 mm removed more nitrate and nitrite than Buffalo grass 609 (*Buchloe dactyloides*), a turf grass with root depth of ~ 100 mm (Barrett et al. 2013). Besides that *Carex* sp. with a dense root architecture and many fine root hairs has been the most favorable plant species for nitrogen removal (Zinger et al. 2013; Bratieres et al. 2008). Payne et al. (2018) investigated 20 plants species which consist of sedges, reeds, trees, and shrubs with various morphological traits, growth rate, biomass allocation, and scale. It was found that extensive root system (high root length, high root surface area, high root mass, and high length of fine roots ($d < 0.25$ mm) as well as high total biomass are the critical traits to TN and nitrate removal. These traits provide effective contact between root and infiltrated stormwater through the filter which influence plants growth and their nutrients uptake.

The presence of plants in the bioretention cell can increase TP retention in unsaturated media (Lucas and Greenway 2008). Vegetative mesocosms were found to be more effective in removal of P at the longest hydraulic residence times (Liu et al. 2014b). A study in Korea concluded that *Rhododendron indicum* Linnaeus gives the greatest TP uptake (Geronimo et al. 2014). However, there was a different view by Glaister et al. (2014) who revealed that the presence of plants has a significant effect on phosphate removal but not TP, as phosphate is chemically and biologically driven, while TP removal is primarily related to the removal of total suspended solids (TSS). Nevertheless, type of plant does not give a significant effect to the efficiency of P removal (Muerdter et al. 2018), but it appears to be significant in limiting clogging problem (Le Coustumer et al. 2012). In reducing clogging problem, thick roots are suggested as it is able to increase hydraulic conductivity and minimize the overflows which leads to maintaining efficient pollutants removal (Muerdter et al. 2018; Le Coustumer et al. 2012). A study of Le Coustumer et al. (2012) revealed that bioretention tend to clog over time, and plants species with thick roots (*Melaleuca ericifolia*) helped in reducing clogging problem.

The climatic condition is different across various regions where tropics receive high rainfall while temperate regions face prolonged dry period and seasonal winter. Hence, the plants' selection criteria for tropical and temperate regions should be different. As shown in Table 5, *Carex*, *Melaleuca*, and *Juncus* spp. are widely used in past studies due to their effectiveness in reducing the concentration of some pollutants (Read et al. 2008). In temperate countries such as Australia and the USA, *Carex apressa*, a native sedge species, is one of the most commonly used species for bioretention studies due to its adaptability in dry and wet regimes (Bratieres et al. 2008; Zinger et al. 2013). Zhang et al. (2011b) recommended that the selected native species such as *B. juncea*, *B. rubiginosa*, *J. subsecundus*, and *M. lateritia* are suitable for being used in biofilters in Western Australia due to their effective nutrient removal.

Although plant species such as grass and sedge are widely used in temperate countries, this kind of species could be invasive in tropical countries, such as Malaysia and Singapore, due to high rainfall, hot and humid climate, as well as high nutrient content in runoff. Possible widespread of sedge and grass in tropical climate may be hard to control as they can re-establish from seeds or remaining roots (Goh et al. 2017). Furthermore, more periodic maintenance is needed for cutting grass or sedge as they tend to spread very quickly due to frequent rainfall. Therefore, it is not advisable to use the sedge and grass in tropical biofilters due to their invasive behavior.

In tropical climates, the ability of plants to tolerate dry weather and short-term inundation are the key factors in selection of plant, thus hardy plant species was recommended.

**Table 5** Reported types and classification of plants used in bioretention laboratory studies

| Country | Plant species | Plant type | Remark | Author |
|---|---|---|---|---|
| Australia | *Carex appressa*<br>*Melaleuca ericifolia*<br>*Microlaena stipoides*<br>*Dianella revoluta*<br>*Leucophyta brownii* | Grass<br>Shrub<br>Grass<br>Herb<br>Shrub | *C. appressa* and *M. ericifolia* appeared to be effectively remove nitrogen. | Bratieres et al. (2008) |
| | *Carex appressa*<br>*Lomandra longifolia* | Grass<br>Grass | Plantings incorporating *C. appressa* and *L. longifolia* in biofilters can improve pollutant removal over a monoculture of L. longifolia. | Ellerton et al. (2012) |
| | *Baumea juncea*<br>*Melaleuca lateritia*<br>*Baumea rubiginosa*<br>*Juncus subsecundus* | Grass<br>Shrub<br>Grass<br>Grass | • TN removal was significantly higher in the planted treatments with SZ than without SZ.<br>• TN removal was significantly higher in *M. lateritia* without SZ compared to *B. juncea* without SZ. | Zhang et al. (2011b) |
| | *Dianella revoluta*<br>*Microlaena stipoides*<br>*Carex appressa* | Herb<br>Grass<br>Grass | The biofilter columns planted with *D. revolute* and *M. stipoides* showed poor N removal, while biofilters planted with *C. appressa* were performing well. | Zinger et al. (2013) |
| USA | Buffalo grass<br>Big Muhly | Grass<br>Grass | The columns without plants were found to export substantial amounts of nitrate/nitrite, whereas the columns with the plants demonstrated a substantial removal of nutrients (59–79% of the total nitrogen and 77–94% of the total phosphorus). | Barrett et al. (2013) |
| | *Festuca arundinacea*<br>*Echinochloa crus-galli*<br>*Digitaria sanguinalis*<br>*Panicum dichotomiflorum* | Grass<br>Grass<br>Grass<br>Grass | • The bioretention medium composed of 15% mix of coir and peat, 9% shredded hardwood mulch, 12% water treatment residue (WTRs), and 58% sand (by volume) removed the highest amount of total *P* (> 95%), which is attributed to the high quantity of WTRs.<br>The highest TP removal was achieved at hydraulic residence times of 6 h. | Liu et al. (2014b) |
| USA | *Pennisetum alopecuroides*<br>*Dianella brevipedunculata*<br>*Banksia integrefolia*<br>*Callistemon pachyphyllus* | Grass<br>Grass<br>Shrub<br>Shrub | TP retention in the vegetated loam was 91% compared to 73% in the barren, and TN retention was 81% compared to 41% in the barren loam. | Lucas and Greenway (2008) |
| | *Betula* and *Magnolia*<br>*Viburnum* and *Itea*<br>*Helianthus* and *Eupatorium*<br>*Panicum*<br>*Juncus* | Tree<br>Shrub<br>Shrub<br>Grass<br>Grass | • The woody *B. nigra* and its cultivar stored the most N and P per specimen and per cost per unit canopy area.<br>• The herbaceous species *P. virgatum* and *H. angustifolius* sequestered the most N and P per unit area.<br>• However, if both low-cost per nutrient uptake and high-nutrient uptake per area are desired, then three species appear to be the optimal choices: *P. virgatum*, *P. Shenandoah*, and *E. Gateway.* | Turk et al. (2017) |
| Korea | *Buxus microphylla* | Tree | This study revealed that the nitrate leaching was caused by nitrification during dry days | Cho et al. (2009) |
| | *Chrysanthemum zawadskii*<br>*Aquilegia flabellate*<br>*Rhododendron indicum*<br>*Spiraea japonica* | Shrub<br>Shrub<br>Shrub<br>Shrub | Rhododendron indicum Linnaeus was identified as the most appropriate plant that should be used in bioretention systems considering factors such as number of flower per plants, plant decay<br>Rate, cost of plant, number of plants per reactor, and TN and TP uptake by plants. | Geronimo et al. (2014) |
| Singapore | *Elateriosperrnun tapos* | Tree | *E. tapos* Blume tree saplings have potential for the phytoremediation of nitrate and phosphate found in urban stormwater in Singapore. | Chen et al. (2014) |
| Malaysia | *Hibiscus rosa-sinensis* | Shrub | • The results showed that media enhanced with shredded newspaper demonstrated a significant improvement in TN removal (80.4%), compared to standard bioretention media (57.5%) without compromising TSS and TP removal, when dosed with actual runoff.<br>• The thick root system and rapid growth rate of the plant were proven to contribute to TN removal. | Goh et al. (2017) |

Besides, with the frequent rainfall, the vegetated bioretention system should be able to support more variety of plants such as shrubs and trees with various root systems to uptake different types of pollutants. As stormwater runoff in developing countries consists of high nutrient concentration, the role of vegetation to uptake excessive nutrients is crucial. A tropical shrub *Hibiscus rosa-sinensis* has been recommended in tropical country as it is a fast-growing and easy-to-propagate native tropical shrub (Goh et al. 2017). In another study conducted by Chen et al. (2014), *E. tapos* plants were found a good phytoremediator for both nitrate and phosphate in bioretention systems. In Korea, the shrub species (*R. indicum* and *S. japonica*) and tree species (*B. microphylla*) has been used to investigate the removal of nutrients in bioretention systems (Cho et al. 2009; Geronimo et al. 2014).

Research also showed that maximal nutrients removal would be achieved by planting different suitable species with complementary effects within the same system. Ellerton et al. (2012) revealed that mixed planting of *C. appressa* and *L. longifolia* can improve pollutants removal over monoculture of *L. longifolia.* Further research is required to investigate the effectiveness of using mixture of different plants species on nutrient removal in tropical bioretention systems. To conclude, there is a lack of studies on plants selection for tropical bioretention systems, their efficiency in nutrient removal, and their maintenance requirement; therefore, more research is required to fill these gaps of knowledge in developing and implementing bioretention systems in tropical countries.

### Performance with submerged zone

Researchers have suggested using submerged zone in bioretention, as it is essential for plants and microbes survival during prolonged dry periods, and able to create an anoxic condition which could facilitate nitrogen removal (Payne et al. 2015; Glaister et al. 2014; Zinger et al. 2013; Zhang et al. 2011b). The problem of the reduction of pollutants uptake by plants during dry periods in temperate countries has been mitigated with submerged zone (LeFevre et al. 2014). Bioretention systems with submerged zone also enhance plants growth, improve denitrification, and increase removal of total dissolved nitrogen (TDN) and TN (Zhang et al. 2011b). Table 5 shows the results of laboratory studies conducted in the USA and Australia incorporating the use of submerged zone in bioretention system. The study of Palmer et al. (2013) concluded that the utilization of saturated zone enables better removal of nitrate with 71% rate compared to 33% rate which was resulted for a bioretention system without saturation zone. The study of Gilchrist et al. (2013) also confirmed higher removal rate of nitrate and nitrite (75%) in a system with submerged zone compared to 7% resulted from a system without saturation zone. However, the presence of saturation zone significantly decreases ammonia-N reduction (Gilchrist et al. 2013).

Certain criteria need to be fulfilled to obtain the benefit from incorporation of the submerged zone. Barrett et al. (2013) found that submerged zone does not have influence on evapotranspiration rate due to the limited thickness (150 mm). Zinger et al. (2013) also reported that a minimum submerged zone depth of 450 mm is needed for denitrification to occur. It is worth mentioning that TP removal becomes less efficient with submerged zone due to the presence of organic matters in the filter media within the submerged zone (Barrett et al. 2013). Although there are lack of studies in tropical countries that included submerged zone in their researches, N and P removal in bioretention basin without submerged zone has been still promising (Goh et al. 2017; Guo et al. 2014). Like any landscape feature, bioretention systems must be maintained through pruning and watering. A bioretention maintenance guideline published by Hunt et al. (2015) recommended watering of plants every 2 to 3 days until a rainy period if the plant establishment occurs near a drought period. This has indicated that submerged zone is not a critical component for bioretention in tropical climate.

There were several factors to be considered for application of submerged zone in bioretention systems in tropics. Goh et al. (2017) suggested the use of submerged zone becomes inappropriate in tropical climates due to their different rainfall regime. As tropical countries have average annual precipitation of 2500 mm, submerged zone becomes less important. Unlike temperate countries where extended dry period is a danger for plants, amount of rainfall in tropical countries is sufficient to support the plants' growth all around the year. Besides, soil moisture could be maintained due to the higher water table level and high air humidity in tropical regions. Moreover, implementing submerged zone imposes an additional depth for the bioretention which may increase the cost of construction.

## Conclusion

Bioretention system is one of the on-site stormwater management solutions (solutions at the source) that has been widely implemented in temperate countries such as the USA and Australia while it has been getting attention in tropical countries such as Singapore and Malaysia. There were plenty of researches conducted in the USA and Australia, providing substantial data and findings on the design components and the overall performance of bioretention systems. Based on aforementioned studies, guidelines are developed in temperate countries which may not be suitable for being used in tropical countries due to several reasons including geographical and climatic differences. In fact, the research studies on tropical bioretention systems have been relatively insufficient, thus the implementation of bioretention systems and achieving the targeted design goals are uncertain. Therefore, the major differences between temperate countries and tropics including rainfall amount and patterns, runoff generation processes, nutrients concentration, and land use need to be considered in developing a design guideline that can cater bioretention systems design in tropics. This review study provides the following suggestions and recommendations for future research studies which are aimed to enhance the bioretention systems design and their performance in tropical regions:

- It is recommended to adopt certain pollutants concentration (mg/L) for system's effluent rather than considering percent removal (%) as a criterion to measure the performance of a bioretention system.
- Usage of mulch layer is not recommended for tropical regions as rainfall amount in tropics is sufficient to provide reasonably good soil moisture that can support the plants' growth. Moreover, the usage of mulch layer in tropics may lead to the problem of scouring and flotation of mulch in the system due to the fact that tropical regions often receive large amount of stormwater in a short period of time.
- Usage of submerged zone is not recommended in tropical bioretention systems. This is due to the fact that the amount of rainfall in tropical countries is sufficient to support the plants' growth all over the year.
- Usage of suitable additives can help in nutrient removal. Promising additives tested in bioretention systems for nutrients removal in tropical countries are newspaper and water treatment residuals (WTR). However, further research studies are still needed to suggest more suitable additives and provide more quantitative measures on their usage and performance to maximize their role in pollutants removal.
- Usage of suitable local plants are recommended for tropical bioretention systems as plants have good potential to (1) improve nutrients removal by their nutrient uptake, (2) slow down the horizontal flow, and (3) maintain a reasonable infiltration rate in filter media by help of their roots that can limit the clogging problem. Plants species classified as grass and sedge, which are normally used in temperate countries, are not suitable in the tropics as they are invasive and hard to control upon widespread. Therefore, more studies on tropical shrubs are necessary.
- It is recommended to incorporate soil faunas in tropical bioretention systems as there are clear possibilities that the presence of soil fauna in bioretention systems will change laboratory-based estimation on bioretention systems performance in the field. The performance of bioretention system facilitated with soil faunas remains an open research area. The influences of soil fauna in bioretention systems in the tropics should be studied.

**Funding information** This work was supported by the Division of Research & Innovation, Universiti Sains Malaysia under the grant title of "Influence of Enhanced Bioretention Media and Tropical Shrub on Nutrient Removal for Urban Runoff in Mixed Development Area: An On-Site Study" with grant number as: 203/PKT/6720004.

## References

Adugna AT, Andrianisa HA, Konate Y, Ndiaye A, Maiga AH (2015) Performance comparison of sand and fine sawdust vermifilters in treating concentrated grey water for urban poor. Environ Technol 36:2763–2769

Ayers EM (2009) Pedogenesis in rain gardens: the role of earthworms and other organisms in long-term soil development, University of Maryland, College Park

Barrett ME, Limouzin M, Lawler DF (2013) Effects of media and plant selection on biofiltration performance. J Environ Eng 139:462–470

Blecken G, Zinger Y, Muthanna TM, Deletic A, Fletcher TD, Viklander M (2007) The influence of temperature on nutrient treatment efficiency in stormwater biofilter systems. Water Sci Technol 56:83–91

Bratieres K, Fletcher T, Deletic A, Zinger Y (2008) Nutrient and sediment removal by stormwater biofilters: a large-scale design optimisation study. Water Res 42:3930–3940

Brown R, Hunt W (2011) Underdrain configuration to enhance bioretention exfiltration to reduce pollutant loads. J Environ Eng 137:1082–1091

Brown RA, Hunt WF III (2010) Impacts of media depth on effluent water quality and hydrologic performance of undersized bioretention cells. J Irrig Drain Eng 137:132–143

Carpenter DD, Hallam L (2009) Influence of planting soil mix characteristics on bioretention cell design and performance. J Hydrol Eng 15: 404–416

Chapman C, Horner RR (2010) Performance assessment of a street-drainage bioretention system. Water Environ Res 82:109–119

Chapuis-Lardy L, Le Bayon RC, Brossard M, López-Hernández D., Blanchart E (2011) Role of soil macrofauna in phosphorus cycling. Phosphorus in Action. Springer

Chen X, Peltier E, Sturm BS, Young CB (2013) Nitrogen removal and nitrifying and denitrifying bacteria quantification in a stormwater bioretention system. Water Res 47:1691–1700

Chen XC, Huang L, Ong BL (2014) The phytoremediation potential of a Singapore Forest tree for bioretention systems. J Mater Sci Eng A 4: 220–227

Cho KW, Song KG, Cho JW, Kim TG, Ahn KH (2009) Removal of nitrogen by a layered soil infiltration system during intermittent storm events. Chemosphere. 76:690–696

Chow M, Yusop Z (2014) Characterization and source identification of stormwater runoff in tropical urban catchments. Water Sci Technol 69:244–252

Colloff MJ, Pullen KR, Cunningham SA (2010) Restoration of an ecosystem function to revegetation communities: the role of invertebrate macropores in enhancing soil water infiltration. Restor Ecol 18:65–72

Davis AP (2007) Field performance of bioretention: water quality. Environ Eng Sci 24:1048–1064

Davis AP, Shokouhia M, Sharma H, Minami C (2006) Water quality improvement through bioretention media: nitrogen and phosphorus removal. Water Environ Res 78:284–293

Davis AP, Hunt WF, Traver RG, Clar M (2009) Bioretention technology: overview of current practice and future needs. J Environ Eng 135: 109–117

DEP (2006) Pennsylvania stormwater best management practices manual. Pennsylvania Department Of Environmental Protection, US

DID (2012) Urban stormwater management for Malaysia, 2nd edn. Malaysia Department of Drainage and Irrigation (DID) Malaysia, Kuala Lumpur

Dietz ME (2007) Low impact development practices: a review of current research and recommendations for future directions. Water Air Soil Pollut 186:351–363

Dietz ME, Clausen JC (2006) Saturation to improve pollutant retention in a rain garden. *Environmental Science and Technology*, 40:1335–1340

DOE (2012) Malaysia environmental quality report. Strategic Communication Division, Department of Environment Malaysia (DOE), Putrajaya

Duncan HP (1999) Urban stormwater quality: a statistical review, Ed. Wong, THF, Engineers Australia

Ellerton J, Hatt B, Fletcher T (2012) Mixed plantings of Carex appressa and Lomandra longifolia improve pollutant removal over a monoculture of 'L. longifolia' in stormwater biofilters. WSUD 2012: water sensitive urban design; Building the water sensiitve community; 7th international conference on water sensitive urban design. 2012. Engineers Australia, p 164

Geronimo FKF, Maniquiz-Redillas MC, Kim LH (2013) Treatment of parking lot runoff by a tree box filter. Desalin Water Treat 51: 4044–4049

Geronimo FKF, Maniquiz-Redillas MC, Kim LH (2014) Fate and removal of nutrients in bioretention systems. Desalin Water Treat 53:3072–3079

Gilchrist S, Borst M, Stander EK (2013) Factorial study of rain garden design for nitrogen removal. J Irrig Drain Eng 140:04013016

Glaister BJ, Fletcher TD, Cook PL, Hatt BE (2014) Co-optimisation of phosphorus and nitrogen removal in stormwater biofilters: the role of filter media, vegetation and saturated zone. Water Sci Technol 69: 1961–1969

Goh HW, Zakaria NA, Lau TL, Foo KY, Chang CK, Leow CS (2017) Mesocosm study of enhanced bioretention media in treating nutrient rich stormwater for mixed development area. Urban Water J 14: 134–142

González G, Seastedt TR (2001) Soil fauna and plant litter decomposition in tropical and subalpine forests. Ecology 82:955–964

Guo H, Lim F, Zhang Y, Lee L, Hu J, Ong S, Yau W, Ong G (2014) Soil column studies on the performance evaluation of engineered soil mixes for bioretention systems. Desalin Water Treat 52:3661–3667

Hathaway J, Hunt WF, Wright J, Jadlocki S (2009) Field evaluation of indicator bacteria removal by stormwater BMPs in North Carolina. World environmental and water resources congress 2009: Great Rivers 2009, pp 1–10

Hatt BE, Fletcher TD, Deletic A (2008) Hydraulic and pollutant removal performance of fine media stormwater filtration systems. Environ Sci Technol 42:2535–2541

Hatt BE, Fletcher TD, Deletic A (2009) Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. J Hydrol 365:310–321

Henderson CFK (2009) The chemical and biological mechanisms of nutrient removal from stormwater in bioretention systems. Griffith University

Hermawan AA, Chang JW, Pasbakhsh P, Hart F, Talei A (2018) Halloysite nanotubes as a fine grained material for heavy metal ions removal in tropical biofiltration systems. Appl Clay Sci 160:106–115

Ho C, Tan Y (2013) Pollutant loads of urban runoff from a mixed residential-commercial catchment. World Acad Sci Eng Technol 7: 492–495

Horn MA, Mertel R, Gehre M, Kästner M, Drake HL (2006) In vivo emission of dinitrogen by earthworms via denitrifying bacteria in the gut. Appl Environ Microbiol 72:1013–1018

Hsieh C, Davis A (2005) Evaluation and optimization of bioretention media for treatment of urban storm water runoff. J Environ Eng 131:1521–1531

Hsieh C, Davis AP, Needelman BA (2007a) Bioretention column studies of phosphorus removal from urban stormwater runoff. Water Environ Res 79:177–184

Hsieh C, Davis AP, Needelman BA (2007b) Nitrogen removal from urban stormwater runoff through layered bioretention columns. Water Environ Res 79:2404–2411

Hudak PF, Banks KE (2006) Compositions of first flush and composite storm water runoff in small urban and rural watersheds, north-central Texas. Urban Water J 3:43–49

Hunt WF, Lord WG (2006) Bioretention performance, design, construction, and maintenance. North Carolina Cooperative Extension, Raleigh

Hunt W, Jarrett A, Smith J, Sharkey L (2006) Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. J Irrig Drain Eng 132:600–608

Hunt W, Smith J, Jadlocki S, Hathaway J, Eubanks P (2008) Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte. NC J Environ Eng 134:403–408

Hunt WF, Lord B, Loh B, Sia A (2015) Plant selection for bioretention systems and stormwater treatment practices. Springer

Iqbal H, Garcia-Perez M, Flury M (2015) Effect of biochar on leaching of organic carbon, nitrogen, and phosphorus from compost in bioretention systems. Sci Total Environ 521-522:37–45

Jang A, Seo Y, Bishop PL (2005) The removal of heavy metals in urban runoff by sorption on mulch. Environ Pollut 133:117–127

Jia H, Wang Z, Zhen X, Clar M, Yu SL (2017) China's sponge city construction: a discussion on technical approaches. Front Environ Sci Eng 11:18

Jouquet P, Huchet G, Bottinelli N, Thu TD, Duc TT (2012) Does the influence of earthworms on water infiltration, nitrogen leaching and soil respiration depend on the initial soil bulk density? A mesocosm experiment with the endogeic species Metaphire posthuma. Biol Fertil Soils 48:561–567

Kappes H, Topp W, Zach P, Kulfan J (2006) Coarse woody debris, soil properties and snails (Mollusca: Gastropoda) in European primeval forests of different environmental conditions. Eur J Soil Biol 42: 139–146

Kazemi F, Beecham S, Gibbs J (2009) Streetscale bioretention basins in Melbourne and their effect on local biodiversity. Ecol Eng 35:1454–1465

Kim H, Seagren EA, Davis AP (2003) Engineered bioretention for removal of nitrate from stormwater runoff. Water Environ Res 75: 355–367

Le Coustumer S, Fletcher TD, Deletic A, Barraud S, Poelsma P (2012) The influence of design parameters on clogging of stormwater biofilters: a large-scale column study. Water Res 46:6743–6752

LeFevre GH, Paus KH, Natarajan P, Gulliver JS, Novak PJ, Hozalski RM (2014) Review of dissolved pollutants in urban storm water and their removal and fate in bioretention cells. J Environ Eng 141:04014050

Li L, Davis AP (2014) Urban stormwater runoff nitrogen composition and fate in bioretention systems. Environ Sci Technol 48:3403–3410

Liu J, Davis AP (2013) Phosphorus speciation and treatment using enhanced phosphorus removal bioretention. Environ Sci Technol 48: 607–614

Liu J, Sample DJ, Bell C, Guan Y (2014a) Review and research needs of bioretention used for the treatment of urban stormwater. Water. 6: 1069–1099

Liu J, Sample DJ, Owen JS, Li J, Evanylo G (2014b) Assessment of selected bioretention blends for nutrient retention using mesocosm experiments. J Environ Qual 43:1754–1763

Lucas WC, Greenway M (2008) Nutrient retention in vegetated and nonvegetated bioretention mesocosms. J Irrig Drain Eng 134:613–623

Lucas WC, Greenway M (2011) Hydraulic response and nitrogen retention in bioretention mesocosms with regulated outlets: part II—nitrogen retention. Water Environ Res 83:703–713

Lucke T, Drapper D, Hornbuckle A (2018) Urban stormwater characterisation and nitrogen composition from lot-scale catchments—new management implications. Sci Total Environ 619:65–71

Luell S, Hunt W, Winston R (2011) Evaluation of undersized bioretention stormwater control measures for treatment of highway bridge deck runoff. Water Sci Technol 64:974–979

Luo H, Li M, Xu R, Fu X, Huang G, Huang X (2012) Pollution characteristics of urban surface runoff in a street community. Sustain Environ Res 22:61–68

Mangangka IR, Liu A, Egodawatta P, Goonetilleke A (2015) Performance characterisation of a stormwater treatment bioretention basin. J Environ Manag 150:173–178

MDE (2000) Maryland Stormwater Design Manual. Maryland Department of The Evironment, Maryland

Mehring AS, Levin LA (2015) REVIEW: potential roles of soil fauna in improving the efficiency of rain gardens used as natural stormwater treatment systems. J Appl Ecol 52:1445–1454

Meysman FJR, Middelburg JJ, Heip CHR (2006) Bioturbation: a fresh look at Darwin's last idea. Trends Ecol Evol 21:688–695

MHURC (2014) Technical guidelines on Sponge City construction—low impact development stormwater management system (trial). China Ministry of Housing and Urban-Rural Construction, China

Milandri S, Winter K, Chimphango S, Armitage N, Mbui D, Jackson G, Liebau V (2012) The performance of plant species in removing nutrients from stormwater in biofiltration systems in Cape Town. Water SA 38:655–662

Muerdter CP, Wong CK, LeFevre GH (2018) Emerging investigator series: the role of vegetation in bioretention for stormwater treatment in the built environment: pollutant removal, hydrologic function, and ancillary benefits. Environ Sci Water Res Technol 4:592–612

NJDEP (2009) New Jersey Stormwater Best Management Practices Manual. Chapter four: stormwater pollutant removal criteria. Department of Environmental Protection, Division of Watershed Management, State of New Jersey

NJDEP (2016) New Jersey Stormwater Best Management Practices Manual. Chapter 9.1: bioretention systems. New Jersey Department of Environmental Protection, New Jersey

O'Neill SW, Davis AP (2011) Water treatment residual as a bioretention amendment for phosphorus. II: Long-term column studies. J Environ Eng 138:328–336

Palmer ET, Poor CJ, Hinman C, Stark JD (2013) Nitrate and phosphate removal through enhanced bioretention media: mesocosm study. Water Environ Res 85:823–832

Paus K, Morgan J, Gullive J, Hozalski R (2014) Effects of bioretention media compost volume fraction on toxic metals removal, hydraulic conductivity, and phosphorous release. J Environ Eng 140: 04014033

Payne EG, Pham T, Cook PL, Fletcher TD, Hatt BE, Deletic A (2014) Biofilter design for effective nitrogen removal from stormwater–influence of plant species, inflow hydrology and use of a saturated zone. Water Sci Technol 69:1312–1319

Payne EGI, Hatt BE, Deletic A, Dobbie MF, McCarthy DT, Chandrasena GI (2015) Adoption guidelines for stormwater biofiltration systems. Cooperative Research Centre for Water Sensitive Cities, Melbourne

Payne EGI, Pham T, Deletic A, Hatt BE, Cook PLM, Fletcher TD (2018) Which species? A decision-support tool to guide plant selection in stormwater biofilters. Adv Water Resour 113:86–99

Peterson IJI, Igielski S., Davis AP (2015) Enhanced denitrification in bioretention using woodchips as an organic carbon source Journal of Sustainable Water in the Built Environment 04015004

PGC (2007) The bioretention manual. Environmental Service Div., Department of Environmental Resources, Prince George's County, Maryland

Pop PI, Dîrja M, Dumitraş A (2013) Outdoor experimental mesocosm construction for the evaluation of bioretention in Cluj-Napoca condition. Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Horticulture, p 69

PUB (2011) Engineering procedures for ABC waters design features. Public Utilities Board (PUB), Singapore

PUB (2014) Active, beautiful, clean waters design guidelines, 3rd edn. Public Utilities Board, Singapore

Read J, Wevill T, Fletcher T, Deletic A (2008) Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Research*, 42:893–902

Roy-Poirier A, Champagne P, Filion Y (2010) Review of bioretention system research and design: past, present, and future. J Environ Eng 136:878–889

Shipitalo M, Le Bayon R (2004) Quantifying the effects of earthworms on soil aggregation and porosity. In: Edwards CA (ed) Earthworm ecology, 2nd edn. CRC Press, Boca Raton, pp 183–200

Stander EK, Borst M (2009) Hydraulic test of a bioretention media carbon amendment. J Hydrol Eng 15:531–536

Suárez ER, Pelletier DM, Fahey TJ, Groffman PM, Bohlen PJ, Fisk MC (2004) Effects of exotic earthworms on soil phosphorus cycling in two broadleaf temperate forests. Ecosystems 7:28–44

Suhaila J, Jemain AA (2012) Spatial analysis of daily rainfall intensity and concentration index in peninsular Malaysia. Theor Appl Climatol 108:235–245

Sun X, Davis AP (2007) Heavy metal fates in laboratory bioretention systems. Chemosphere. 66:1601–1609

Taylor M, Clarke W, Greenfield P (2003) The treatment of domestic wastewater using small-scale vermicompost filter beds. Ecol Eng 21:197–203

Trowsdale SA, Simcock R (2011) Urban stormwater treatment using bioretention. J Hydrol 397:167–174

Turk RP, Kraus HT, Hunt WF, Carmen NB, Bilderback TE (2017) Nutrient sequestration by vegetation in bioretention cells receiving high nutrient loads. J Environ Eng 143:06016009

Wang J, Chua LH, Shanahan P (2017) Evaluation of pollutant removal efficiency of a bioretention basin and implications for stormwater management in tropical cities. Environ Sci Water Res Technol 3: 78–91

Water By Design (2014) Bioretention technical design guidelines (version 1.1). Health Waterways Ltd, Brisbane

Wurst S, Langel R, Reineking A, Bonkowski M, Scheu S (2003) Effects of earthworms and organic litter distribution on plant performance and aphid reproduction. Oecologia 137:90–96

Zhang L, Seagren EA, Davis AP, Karns JS (2011a) Long-term sustainability of Escherichia coli removal in conventional bioretention media. J Environ Eng 137:669–677

Zhang Z, Rengel Z, Liaghati T, Antoniette T, Meney K (2011b) Influence of plant species and submerged zone with carbon addition on nutrient removal in stormwater biofilter. Ecol Eng 37:1833–1841

Zinger Y, Blecken GT, Fletcher TD, Viklander M, Deletić A (2013) Optimising nitrogen removal in existing stormwater biofilters: benefits and tradeoffs of a retrofitted saturated zone. Ecol Eng 51:75–82