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Fly ash-amended pervious concrete pavement followed by bamboo bioretention basin with *Dracaena sanderiana* for urban stormwater runoff control

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HIGHLIGHTS

- Optimized pervious concrete pavements were integrated with bamboo bioretention.
- Stormwater runoff volume reduction and water quality performance were determined.
- Leaf chlorophyll and mass of bamboos (*Dracaena sanderiana*) were monitored.
- A PCP-BBB was an effective green infrastructure for stormwater management.

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ABSTRACT

This study assessed the feasibility of pervious concrete pavement (PCP) followed by a bamboo bioretention basin (BBB) with *Dracaena sanderiana* for urban stormwater volume control and water quality enhancement. Two PCPs (nPCP and tPCP) having a permeability of ~4.5 mm/s were prepared with optimized mix designs. A control impervious concrete pavement (CP) was also prepared. Results showed that both PCP-BBB's outperformed CP-BBB not only in runoff volume reduction, but also in pollutant removal; both PCPs removed a considerably high amount of pollutants, especially in fecal coliform and phosphate removal. tPCP-BBB improved water quality better than nPCP-BBB in terms of chemical oxygen demand and pH. Additionally, *D. sanderiana* grew healthier in tPCP-BBB than in nPCP-BBB. Production costs for tPCP and CP were similar, whereas nPCP production was twice as expensive.

1. Introduction

The increased amount of impervious surfaces in urban areas do not allow precipitation to infiltrate into the soil and groundwater, resulting in an increased volume of stormwater runoff. Consequently, this often causes flash flooding of the downstream areas. Urban stormwater runoff may contain high concentrations of non-point source (NPS) pollutants, such as soil particles from construction sites, oil & grease, metals and coolants from vehicles, pathogens (disease-causing microorganisms) from pet wastes and failing septic systems, and nutrients from gardens and homes [1–5].

Among the aforementioned NPS pollutants, the presence of pathogens such as *Salmonella* and *Giardia* in urban stormwater runoff is a serious threat to humans and may result in water body impairment. For example, salmonellosis is one of the most common causes of diarrhea in humans. Globally, there are nearly 1.7 billion cases of diarrheal disease every year and diarrhea kills around 760,000 children under five years old each year [6]. The presence of harmful pathogens in water bodies is tested with indicator microorganisms like fecal coliform (FC).

Nutrient over-enrichment primarily by nitrogen and phosphorous is another NPS pollution of concern in urban stormwater runoff. They promote excessive growth and further decomposition of aquatic plants, resulting in oxygen depletion in water and the growth of toxic cyanobacteria [7].

In addition, automotive fluids are deposited onto road and parking surfaces as NPS pollutants and are prone to transport in urban stormwater runoff to receiving waters. For example, engine coolants and antifreeze containing ethylene glycol and propylene glycol can be toxic and contribute a high concentration of chemical oxygen demand (COD) in urban stormwater runoff [8].

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Evidently, there is a need to control the volume and water quality of NPS pollutant-containing urban stormwater runoff. The use of pervious pavement is among the best management practices (BMPs) for the control of stormwater runoff. Pervious pavement reduces the need for water detention ponds, permits groundwater recharge, decreases or eliminates pollutants from runoff, and improves water quality [9].

A bioretention basin is a landscaped depression where stormwater runoff is collected and the pollutants are captured and biodegraded by biological media such as grass and plants [10]. It is also one of the BMPs for stormwater management. Bamboos can be utilized as biological agents in the bioretention basins due to their unique water retention properties. They are capable of absorbing the most water among the agricultural plants whilst requiring little to no irrigation [11]. Therefore, they are a good, arguably the best, candidate biological agents for stormwater volume and water quality control in locations where intense storm is seasonal, such as in Puerto Rico.

In this study, a combination of two BMPs, a pervious concrete pavement (PCP) and a bamboo bioretention basin (BBB), was assessed for their potential for volume control and water quality enhancement of NPS pollutant-containing urban stormwater runoff. Two statistically optimized PCPs (namely, nPCP and tPCP) and BBB with *Dracaena sanderiana* were evaluated for the reduction of runoff volume and NPS pollution. A control impervious concrete pavement (CP) in combination with BBB (i.e., CP-BBB) was also tested in parallel to PCP-BBB's. A preliminary production cost analysis was done for PCPs and CP and potential influence of PCP's on the growth and health of *D. sanderiana* was evaluated as well.

2. Materials and method

2.1. Materials

The main materials used for the PCPs production were fly ash (FA), Portland cements, nano-sized silica (nanoSiO_2), and coarse aggregates. FA was obtained from a local coal-fueled power plant in Puerto Rico. Type IP Portland cement was used for nPCP production, whereas Type GU Portland cement was used for the production of tPCP and the control CP. Both cements comply with ASTM C595 [12]. The physiochemical characteristics of Portland cements and FA are shown in Table 1.

A commercial nanoSiO_2 was purchased and used as received. It has an average particle size of 20–30 nm and a specific surface area of 180–600 m^2/g. The coarse aggregates used were limestone gravels purchased from a local hardware store. Prior to use, they were sieved to collect the sizes in the range of 4.75–12.5 mm. The mass ratio of coarse aggregates to binder was fixed at 4:1 for the production of PCPs and CP. The binder is defined in this study as the total amount of Portland cement and FA. Fine aggregates (sands) were used only for production of CP in the current study.

Miniature bamboo species (*D. sanderiana*) were used in BBB to accommodate the lab-scale experiment. They were purchased at a local store. The same coarse aggregates aforementioned were used as a supporting medium for *D. sanderiana*.

Tap water was used for rainfall simulation. Treated wastewater effluent (TWE), fertilizer solution, and coolant solution were used as the sources of NPS pollutants of fecal coliform (FC), phosphate (PO_4^--P), and automobile-related COD pollutant, respectively. Treated wastewater effluent was sampled at a local wastewater treatment prior to the chlorination process to ensure FC presence in it. A phosphorus-rich commercial fertilizer was dissolved in deionized water to make desired PO_4^--P concentrations. A commercial antifreeze/coolant solution was diluted with deionized water to make a desired COD concentration. Table 2 shows physiochemical characteristics of rainwater and three NPS waters.

2.2. Production of optimized pervious concrete pavement

tPCP was optimized for 7-day compressive strength and permeability by Response Surface Methodology (RSM) in a two-factor, two-level (2^2) CCD (Table 3). A mechanical mixer was used to prepare the concrete specimens in accordance to the ASTM C192 [16]. For tPCP optimization, mixtures in triplicate were cast in a cylindrical plastic mold (10 cm in diameter × 20 cm in height). The standard rodding consolidation method was used for compaction of each specimen in accordance to the ASTM C192 [16]. The specimens in the mold were immediately put in an individual airtight plastic bag to minimize moisture loss. After a 24-h curing under ambient environment (20–30 °C, unless otherwise specified), specimens were demolded and further cured for 7 days in lime-saturated water under ambient environment. The compressive strength of 7-day cured tPCP specimens was tested in triplicate in accordance to ASTM C39 [17]. The permeability of 7-day cured tPCP specimens was tested by a constant head method modified from ASTM D2434 [18].

For construction of PCPs and CP used in this study in combination with BBB, the optimized tPCP mix was cast in a rectangular wooden mold (9 cm × 20 cm × 5 cm). The same specimen preparation and curing procedures that used for tPCP optimization aforementioned was used. After a 24-h curing under ambient environment, the specimens were demolded. nPCP and CP were also cast in rectangular wooden molds. nPCP was made with (by wt%) liquid-to-binder at 50%, FA-to-binder at 60% and nanoSiO_2-to-binder at 0.04%, with sodium hydroxide (NaOH) solution at 1.71 M as the liquid [19]. The control impervious concrete pavement (CP) was produced with (by vol%) Portland cement (Type GU) at 11%, water at 16%, coarse aggregates at 41% and fine aggregates (sand) at 26%. After a 24-h curing in an airtight plastic bag, nPCP specimen was demolded and cured for 7 days in the same bag [19], whereas CP specimen was demolded and cured for 7 days in lime-saturated water. Like tPCP, both nPCP and CP were cured under ambient environment.

2.3. Construction of PCP-BBB and CP-BBB systems

PCP-BBB systems were reconstructed in plastic containers (28 cm × 17 cm × 14 cm) (Fig. A1 in Appendix A of supplementary data). Each BBB had 10 stalks of *D. sanderiana*. Light was provided for 8 h per day to the bamboos with a 20 W aquarium light that

Table 1
Physiochemical properties of Portland cements and fly ash used in the study.

Properties	Cement type IP	Cement type GU	Fly ash
Mineralogical composition (% wt)			
SiO_2	27.14	19.80	30.84
Al_2O_3	6.68	5.10	9.93
Fe_2O_3	3.71	3.10	5.01
CaO	55.47	67.3	39.61
MgO	1.62	0.8	0.35
K_2O	0.48	–	1.01
Na_2O	0.59	–	0.90
SO_3	3.48	2.7	11.43
TiO_2	0.32	–	0.45
P_2O_5	0.11	–	0.11
Loss-on-Ignition (% wt)[a]	5.52	6.8	7.62
Blaine (m^2/kg)[b]	554	488	441
Fineness (% wt)[c]	92.6	92.5	73.7

[a] The weight loss of the sample due to heating at 900–1000 °C (1650–1830°F) until a constant weight is obtained (ASTM C114) [13].
[b] A measurement of the surface area of the sample, that is referred to as a fineness measure (ASTM C204) [14].
[c] Wet sieve percentage passing the No. 325 (45 μm) sieve (ASTM C430) [15].