Permeable Pavement Systems for Stormwater Management

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There has been growing interest in the field of permeable pavement systems (PPS), especially in the scope of stormwater management as a sustainable urban drainage system (SUDS). Slight modifications within the PPS layers or incorporation of innovative filters could result in improved contaminant removal efficiency. In addition maintenance procedures were proven effective in mitigating clogging effects, mostly occurring at the upper 1.5–2.5 cm of the PPS. Although partial replacement of the PPS mix design with recycled aggregates improved the overall permeability, the compressive strength was slightly compromised.

Keywords: permeable pavement systems ; stormwater management ; performance ; recent developments ; stormwater quality

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1. Introduction

The continuous increase in global temperatures due to the emissions of greenhouse gases, such as carbon dioxide, has led to various climate change impacts and environmental issues [1][2]. This has caused increased frequency and duration of extreme weather events, resulting in increased rainfall and short-duration intensity [3][4][5]. In addition, the rise in the use of impervious surfaces due to rapid urbanization has also resulted in increased stormwater runoff, peak flows, and a reduced infiltration rate [6]. Stormwater runoff can carry different pollutants, including heavy metals, nutrients, and polyaromatic hydrocarbons (PAHs), resulting in groundwater and soil contamination [7][8]. These pollutants may also result in eutrophication or algal blooms in the receiving water bodies [9]. Furthermore, ineffective management of stormwater runoff may overload the sewerage systems and result in localized flooding events [10]. Therefore, there has been increasing interest in sustainable stormwater management practices.

Different practices have been developed to reduce stormwater runoff and improve its quality. These practices can be classified as sustainable urban drainage systems (SUDS) and include techniques such as permeable surfaces, filter and infiltration trenches, retention basins, wetlands, ponds, and water harvesting [11]. One of the most promising SUDS is permeable pavement systems (PPS). They are considered viable options due to their structural, economic, and road-user benefits. However, the challenges in the practical implementation of SUDS are due to constraints related to construction costs, characteristics of the land, long-term performance, and technical difficulties in installation and maintenance [11].

Some literature reviews have already discussed the different materials used to construct PPS [12][13][14][15]. However, this entry highlights trends in this field of research, and discusses the recent advances in improving the performance of PPS.

2. Background

There are mainly three types of PPS: pervious concrete, porous asphalt, and permeable interlocking concrete pavers (PICP) [16][17]. Depending on the site and soil conditions, they could be full infiltration, partial infiltration, or no infiltration (full exfiltration), mainly used for low-permeability or clay subgrade soils [18]. These permeable pavements share similar benefits in mitigating stormwater quality impacts. Meanwhile, few studies on PPS have typically focused on evaluating the strength, permeability, design configurations, water quality parameters, stormwater harvesting, groundwater recharge, water reuse, and life cycle assessment (LCA) [15][19][20][21][22][23]. Kia et al. and Mishra et al. have evaluated factors that affect the clogging of PPS, including physical clogging such as the entrapment of fine particles within the pores of the structure, chemical clogging that relates to the formation of scale, and biological clogging due to the accumulation of bacteria and algae or penetration of plant roots [24][25]. These factors were found to reduce the overall functionality of PPS, limit their hydrological performance, and decrease the infiltration capacity. Other factors that were reported to affect clogging in PPS are the size of pollutants present, concrete mix design, the pore structure arrangement, and permeability [26]. In terms of subgrade characteristics, it was found that the presence of clayey soil results in low bearing capacity and low hydraulic conductivity, which affects the exfiltration rate, lag times and the strength of the permeable pavement with time [26].

In addition, some practical field investigations have been conducted by many researchers to simulate the performance and infiltration capacities of different permeable pavements in Australia and the Netherlands. It was reported that although the infiltration capacity of the PPS tended to decrease with time due to the buildup of sediments, poor maintenance, and installation, almost 90% of the 55 pavements (ranging from 1 to 12 years of age) tested had surface infiltration rates that satisfied the infiltration rate standards [18][27]. Another study in Santa Catarina, Brazil, collected stormwater from PPS parking lots and concluded that such systems could save up to 54% in potable water [28]. In Florianopolis, Brazil, stormwater harvesting from permeable pavements was implemented and resulted in potable water savings of up to 19.4, 70.0, and 75.7% in the residential, commercial, and public sectors, respectively [19]. In Melbourne, Australia, there has been a tendency and growing popularity toward rainwater harvesting for domestic purposes ever since the city encountered severe drought for several successive years [21][29].

Few investigations have considered PPS performance in improving stormwater quality. Although several research studies discussed stormwater reuse for potable/non-potable uses for PPS, few articles evaluated their water quality performance [30][31][32][33]. In terms of stormwater quality, there has been some literature that has addressed the benefits of PPS in reducing significant contaminants such as turbidity, total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), heavy metals, oils, and hydrocarbons [34][35][36][37]. A study in Reze, France, investigated removal efficiency from stormwater pollutants runoff to permeable pavements, which resulted in respective reductions of approximately 59, 84, 77, and 73% for TSS, Pd, Cd, and Zn (heavy metals) when passed through PPS [31]. Another study evaluated the efficiency of PPS with swale to remove yearly pollutant runoff from a 4.65-hectare parking lot in Florida. It was revealed that the system achieved around 75 to 94% removal rates of solids and metal loads [38]. Furthermore, long-term monitoring performed in a section of a road in Auckland resulted in a reduction of around 95% for total zinc loads and 70% for TSS [39].

Therefore, it is important to highlight recent advancements in the field and research opportunities that could be further investigated to improve the performance of PPS.

3. Recent Developments

The main distinctive themes in the research topic of PPS for stormwater management are as follows: (1) improving and predicting the removal of contaminants, (2) characterizing and minimizing the effects of clogging, (3) improvements for infiltration rate (IR) assessment and characterization, and lastly, (4) sustainability considerations. Therefore, it is pertinent to highlight recent advancements to overcome challenges in each of the identified research themes. This would, in turn, allow for identifying knowledge gaps and future research opportunities. **Table 1** depicts some of the major recent advancements along with the research opportunities that researchers could address in their future investigations.

Table 1. Recent advancements and research opportunities.

Research Theme	Recent Advancement	Research Opportunity
Improving and predicting the removal of contaminants	• Mixing sorbent materials such as pozzolanic materials [40], photocatalytic nanomaterials, and iron oxides [41][42][43], replacing sand and gravel layer with coal gangue [44], biofilms for removal of mercury [45], bentonite [46], diatomite and zeolite powder [47] • Structural modifications, such as: increasing the number of layers and their thicknesses [48], a combination of different layers with varying properties [49], the inclusion of an internal water storage zone [32][33][50], multifunctional green-pervious concrete (MGPC) to remove PAHs contaminants [51]. • Predicting contaminant removal: modeling contaminant removal rates by regression analysis [52].	• Assessing the long-term performance of PPS for: ◦ Water quality enhancement ◦ Leaching of adsorbed contaminants ◦ Possibility of simplifying the PPS system to be implemented by another research. ◦ Limiting the number of contaminants investigated and detailed focus on the effect of certain contaminants on clogging. ◦ Focus on the effectiveness of PPS in removing emerging contaminants
Characterizing and minimizing the effects of clogging	• Relating clogging to maintenance effectiveness: clogging usually affects the top 1.5–2.5 cm of the PPS system [53][54][55][56] and hence vacuum sweeping and/or pressure washing are the most common and [57] effective methods for increasing IR [56][57][58]. In addition, maintenance is not required when IR is greater than 250 mm/min [59]. • Accurate characterization of clogging such as X-ray CT for analyzing pore network, computational fluid dynamic (CFD) to predict hydraulic conductivity [60][61], utilizing 2D and 3D microtomography techniques to visualize clogging [62][63], water content reflectometers (WCR) and time domain reflectometers (TDRs) [64], regression analysis and artificial neural networks (ANN) to predict clogging by means of lab experiments [65][66]. • Modeling of clogging dynamics such as: determining and predicting hydraulic conductivity and pore-clogging using regression analysis, discrete element modeling, and the Kozeny–Carman model [67][68][69][70].	• Develop a standardized clogging test that researchers can adopt and implement to compare their results. • In addition to sediments, exposing the PPS systems to a wide variety of pollutants and clogging materials to assess the clogging effect. • Investigate different chemical or biological techniques that could be more effective in removing soluble contaminants. • Emphasize the use of numerical modeling along with experiments to verify clogging effects and predict optimal porosities and pore size. • Investigating deep layers of PPS using advanced imaging techniques to attribute the observed effects on IR and hydraulic conductivity.

Research Theme	Recent Advancement	Research Opportunity
Improvements for IR assessment and characterization	• Enhancements for PPS field tests: large infiltration rings (>200 mm) are recommended for accurate assessment of field infiltration tests [71][72]. PC slab specimens are more representative of field conditions than cylindrical specimens [24][73]. • Modifying PPS structure, such as coarse aggregates with copper slag or inclusion of a high-permeability media mixture (HPMM) increases porosity, permeability rate, and infiltration rate [50][74][75], reducing fine aggregates from 0% to 100% from concrete mix design increases IR significantly [76].	• Comparing results from previous literature to assess the feasibility and conduct LCA for the long-term monitoring of such modifications. • Investigate the effect of different rainfall intensities on the IR and the impact it may cause with varying dry and wet weather conditions.
Sustainability Considerations	• Focus on cement replacement such as a combination of PA mix (PAC) and permeable cement mix (PCC) with varying layers and structural thicknesses [48], recycled asphalt pavement (RAP) aggregate [77], incorporation of sugar cane bagasse ash (SCBA) pozzolanic materials [40][78], recycled fine aggregates [79], GGBS [80], and construction and demolition (C&D) materials [81]. • Life cycle analysis (LCA): energy and cost assessment based on the transport and operational energy of the PPS and LC cost assessment based on the main and subcomponents for the construction of PPS [10][82].	• Including life cycle assessment and relying on advanced inventories such as (SimaPro and Ecoinvent) in terms of construction costs, acquisition of materials, feasibility studies, cost savings, and overall environmental impact. • Importance of incorporating stormwater harvesting and continuous monitoring of such systems to determine any degradation in the water quantity or quality, especially for areas prone to drought.

In addition to **Table 1**, it is important to emphasize certain elements that were previously discussed in the bibliometric analysis. For instance, most of the clogging tests were performed by either evaluating the infiltration rates or permeability. The most common IR tests are ASTM C1701 and ASTM C1781 for PC and PICP, respectively [26][55][64][83][84]. In addition, falling head and constant head permeability tests were used to assess the clogging effect of different materials by measuring their permeability over a simulated time period [62][85]. Although some infiltration and permeability tests follow Darcy's laminar flow regime, this may not be valid for some PPS applications, and hence modifications of such equations have been addressed by some authors [73][86][87]. Furthermore, in the articles that conducted clogging experiments, the sediment loadings were not specified, with some either evaluating sand and/or clay with different proportions. Therefore, it is essential to have a benchmark and consistent sediment loadings for other researchers to follow and compare the findings. Furthermore, it is worth mentioning that the conclusions relevant to clogging effects in PPS varied and conflicted across different articles. Some authors reported that sand sediments did not substantially reduce the permeability, whereas others concluded that sand particles were a major contributor to clogging [24]. Such anomalies need to be addressed and discussed in detail when performing future investigations.

Moreover, some articles explained that the removal efficiency of selected contaminants in PPS was enhanced with an increase in the pH values (> 8.0) [41][85][88]. However, there could be a set of drawbacks when such effluents are to be discharged into natural or ground water bodies and may have a negative effect on the environment. Therefore, modifications to the concrete mix design, stabilization of the pH, or additional secondary treatments could be employed in the future.

Other interesting findings observed that the reductions in runoff volumes were greatly reduced from 70 to 90% when transitioning from a relatively wet climate to a relatively drier one [89]. Yet, such a conclusion was limited to one article. Therefore, future investigations could incorporate additional parameters when evaluating PPS, including weather and climatic data conditions, such that researchers could adopt an optimal design depending on the site location and weather conditions.

Although infiltration rates tended to increase with increased rainfall intensities, such pavements deteriorated over time and required frequent service and maintenance [64][90]. Experimental investigations regarding the variations in cross slope, longitudinal slope, and rainfall intensity with respect to infiltration rate are of great importance, especially for terrain areas [90]. Therefore, continuous research on such aspects is essential for effective planning and designing in large-scale construction.

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