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Review

Permeable Pavements Life Cycle Assessment: A Literature Review

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Abstract: The number of studies involving life cycle assessment has increased significantly in recent years. The life cycle assessment has been applied to assess the environmental performance of water infrastructures, including the environmental impacts associated with construction, maintenance and disposal, mainly evaluating the amount of greenhouse gas emissions, as well as the consumption of energy and natural resources. The objective of this paper is to present an overview of permeable pavements and show studies of life cycle assessment that compare the environmental performance of permeable pavements with traditional drainage systems. Although the studies found in the literature present an estimate of the sustainability of permeable pavements, the great heterogeneity in the evaluation methods and results is still notable. Therefore, it is necessary to homogenize the phases of goal and scope, inventory analysis, impact assessment and interpretation. It is also necessary to define the phases and processes of the evaluation, as well as the minimum amount of data to be considered in the modelling of life cycle assessment, in order to avoid heterogeneity in the functional units and other components. Thus, more consistent results will lead to a real evaluation of the environmental impacts caused by permeable pavements. Life cycle assessment studies are essential to guide planning and decision-making, leading to systems that consider increasing water resources and reducing natural disasters and environmental impacts.

Keywords: permeable pavements; life cycle assessment; stormwater management; sustainability

1. Introduction

The increase in the frequency of flooding in urban areas related to the increase of impermeable surfaces highlights the inadequacy of traditional urban drainage systems. According to Min et al. [1], it is expected that the frequency of high intensity and short duration rainfall events will increase in the coming decades as a consequence of climate change. Wasko and Sharma [2] identified a strong correlation between peak precipitation intensity and high temperatures, and concluded that global warming may lead to an increase of floods of short duration. In addition, Luo et al. [3] report that flash floods have occurred more frequently in Asian cities, with recent increases in urbanization and extreme rainfall, causing significant damage to infrastructure, communities and the environment. This increase in the number of floods shows that it is necessary to use sustainable urban drainage systems capable of restoring the natural hydrological cycle in urban areas and allowing an increase in evapotranspiration and infiltration capacity. Permeable pavements are examples of systems that fulfill this function [4].

According to Scholz and Grabowiecki [5], the management of stormwater in urban areas was observed in a more ecological way due to the emergence of sustainable drainage systems that collect, store, treat and redistribute or recycle water. Compared to the traditional drainage system, stormwater retention and infiltration is a sustainable and cost-effective process, which is suitable for urban areas.

In addition, these systems have benefits such as the reduction of runoff, groundwater recharge, saving water through recycling, and preventing pollution.

Permeable pavements are considered sustainable drainage systems because they are pavements that support the demands of mechanical efforts and at the same time allow the percolation and temporary accumulation of water, reducing surface runoff without causing damage to their structures [6]. Several studies have shown the advantages of using this type of pavement. In comparison to conventional pavements, permeable pavements provide runoff reductions of up to 42% [5]. According to Pagotto et al. [7], the quality of stormwater is improved by the use of permeable pavements for most pollutants. Heavy metals are reduced by up to 74%, solids are retained at a rate of 87% and hydrocarbons are intercepted at an even higher rate (90%).

Brattebo and Booth [8] examined the long-term efficacy of four permeable pavement systems in the United States. The study showed a significantly better performance for permeable pavements, both for water quality, which had lower toxic levels, and for stormwater infiltration. In the four systems, practically all of the precipitation was infiltrated. The levels of copper and zinc obtained in the water samples collected from the conventional asphalt concrete runoff were alarming: toxic concentrations were reached in 97% of the samples. However, in 31 out of 36 water samples infiltrated in permeable pavements, the concentrations were below the detectable toxic level.

According to Maiolo et al. [9], there is a need to have a methodology capable of providing an accurate estimate of the sustainability of drainage systems. In fact, this assessment may not only be tied to environmental benefits related to lifespan, but assessments are necessary in the steps that precede and follow the lifespan. A valid criterion for the verification of the sustainability of a product or system is the life cycle assessment (LCA). LCA presents an opportunity to evaluate and compare projects and choose the most appropriate drainage systems, quantifying a variety of environmental impacts and benefits. LCA has been effectively applied to assess the environmental performance of the water infrastructure, including the environmental impacts associated with the construction, maintenance and disposal of various green infrastructure technologies, such as permeable pavements [10]. This assessment is based primarily on the amount of greenhouse gas emissions, as well as the consumption of energy and natural resources. Some parameters significantly affect the evaluation, such as local climatic patterns, regulatory requirements, quality of infiltrated stormwater, lifespan and treatment efficiency of the systems [11].

As stated by the Electric Power Research Institute [12], at a national scale, the transport and treatment of water and wastewater accounts for nearly 4% of the US electricity demand. Such dependency of water infrastructure on electric utility infrastructure leads to serious environmental impacts. In this way, decentralized water management brings benefits not only as a means of reducing stresses on the water treatment infrastructure but also as a strategy to reduce the demand that water companies impose on the regional energy system, and on reducing the carbon footprint [13]. As a point of reference, the City of New York [14] estimates that systems of water treatment, supply, and sewage along with the methane escaping into the atmosphere (generated by the sewage treatment process) add up to 17% of New York's greenhouse gas emissions.

De Sousa et al. [15] evaluated the environmental performance of green infrastructures (permeable pavements and bioretention basins) by comparing them to water storage and treatment scenarios using traditional drainage systems (grey infrastructure). The results showed that green infrastructures emitted 75% to 95% less greenhouse gases, mainly due to the lower use of electricity during the life cycle. Wang et al. [11] showed by means of a case study in China that 73.48% of energy consumption, 46.70% of greenhouse gas emissions, 98.33% of lead emissions and 99.70% of zinc emissions could be avoided by using permeable pavement instead of conventional pavement.

While understanding the life cycle implications of sustainable drainage systems is only in its early stages, LCA studies are important in guiding planning and decision-making when considering multiple objectives such as increased water resources and reduction of natural disasters and environmental impacts [16]. Thus, the objective of this paper is to present an overview of permeable pavements and show studies of LCA that compare the environmental performance of permeable pavements with traditional drainage systems, in order to provide scientific instructions for the choice of more sustainable drainage systems and thus improve the sustainable management of stormwater in urban areas.

2. Permeable Pavements

2.1. Definition

Permeable pavements are pavements that simultaneously support the demands of mechanical stresses and rolling conditions, whose structure allows the percolation and temporary accumulation of water, reducing surface runoff without causing damage to their structure [17]. In this type of pavement, the structure is composed of a combination of layers, which are: permeable sub-base, permeable base, permeable bedding layer (when applicable) and permeable surface, dimensioned to withstand traffic loading, distribute stresses on the subgrade and allow the percolation of water. The base and sub-base of the pavement consist of open granulometry materials with aggregates that do not contain fines, or with a small amount of fines, resulting in a relatively large void ratio after compaction [18].

Permeable pavements can be modelled with various types of permeable surfaces, such as porous asphalt, pervious concrete, and permeable interlocking concrete [19]. They can be used as an alternative to conventional impervious hard surfaces, such as roads, car parks, footpaths and pedestrian areas [20].

As for the infiltration system, permeable pavements can be designed in three different ways: with total infiltration of the stormwater, partial infiltration or without infiltration, as shown in Figure 1.

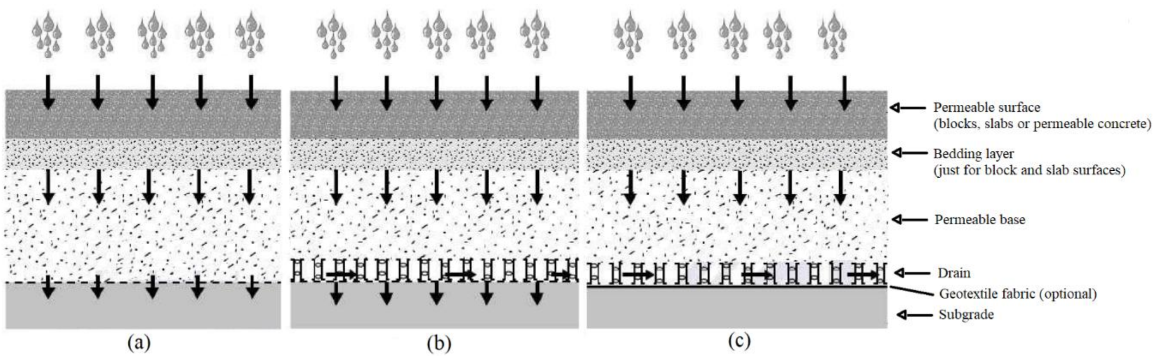

Figure 1. Examples of permeable pavements systems: (**a**) with total infiltration; (**b**) with partial infiltration; (**c**) without infiltration. **Source:** Based on ABNT [17].

2.2. Permeability, Infiltration and Quality of Infiltrated Stormwater

Several studies have demonstrated the benefits of using permeable pavements, such as reducing runoff, groundwater recharge, saving water through recycling and preventing pollution by improving the quality of the infiltrated stormwater [21–26]. The Ramsey-Washington Metro Watershed District [27] conducted a study that aimed to implement a permeable pavement system in a 650 m^2 parking lot in Oregon. The investment was aimed at infiltrating and storing precipitation, reducing runoff from stormwater, maximizing permeability of the area and improving water quality, retaining heavy metals and toxins. The cost for the implantation of permeable pavement was US$102/m^2 and was designed to have 100% infiltration in precipitations of up to 51 mm. Thus, any precipitation up to this figure would not generate runoff. On the other hand, the implementation cost of a conventional pavement system would vary from US$35/m^2 to US$46/m^2, and for this type of pavement the runoff would be 15,000 litres for a 25 mm precipitation.

Legret and Colandini [28] compared the pollution contained in the drainage of stormwater collected from a permeable pavement to the pollution contained in the drainage from a traditional pavement located in the city of Rezé, France. The retentions of suspended solids, lead, cadmium and zinc were, respectively, 59, 84, 77 and 73% higher in the permeable pavement.

Pratt et al. [29] studied the ability of a permeable pavement reservoir structure to retain and treat petroleum-derived pollutants through in situ microbial bio-degradation. The authors constructed a full-scale model permeable pavement in a laboratory. The pavement comprised pre-formed concrete blocks bedded on clean gravel, with vertical drainage provided through gravel-filled inlets between the blocks. A geotextile membrane separated the block bed from the underlying sub-base, comprising 600 mm depth of washed 20–50 mm granite. The entire structure rested on an additional geotextile underlay, supported by a stainless-steel mesh, allowing effluent to flow into a collection funnel located at the base of the tank. The model was subjected to prolonged low-level hydrocarbon contamination, representative of typical loadings to urban surfaces such as highways and car parks. Water quality was monitored by means of oil and grease concentration, chemical oxygen demand (COD), and pH. The retention efficiency of oil in the permeable pavement was 97.6%. The construction materials had a buffering effect, maintaining an effective pH of about 7.0, which is beneficial to microbial growth. With the benefits shown by the results, the study demonstrated that the structure can be used as an effective in situ aerobic bio-reactor. Also, the development of permeable pavements as pollution treatment devices offers a potential solution to the problem of uncontrolled discharge of contaminant loads associated with stormwater.

Pagotto et al. [7] compared the hydraulic behaviour and the quality of the stormwater drained by a section of a highway in the city of Nantes, France, first using a conventional pavement and finally after the replacement of the conventional pavement with a permeable pavement. Regarding the hydraulic behaviour, the permeable pavement system obtained excellent results. Response times (time elapsed between the beginning of the rain and the beginning of the runoff) were, on average, twice as long on this type of pavement. The delay caused the maximum flow rates to be reduced (6.2 litres/s in the conventional pavement and 5.5 litres/s in the permeable pavement) and the discharge time was higher (average discharge duration was 1.15 times greater for permeable pavements).

There was a great difference between the two types of pavements in the quality of the stormwater drained. The percentage of hydrocarbons decreased by 92% and the total suspended solids decreased by 81%. Regarding metals, the reduction ranged from 35% (copper) to 78% (lead). For all metals, the particulate forms are retained at a high rate (greater than 70%). However, metals in the dissolved form are retained with greater difficulty. These results explain the considerable level of retention of zinc, cadmium and lead (mainly present in particle form) by weight in percentage terms and the lower retention of copper (mainly present in dissolved form). The study also showed that in each rainfall event, on average, 0.28 kg of sediment was retained in the permeable pavement, against more than 4.1 kg in the conventional pavement [7].

James [30] has shown that traffic on highways is a major source of pollutants and that these are charged to rivers and streams when precipitation occurs. A survey by the Forth River Purification Board indicates that more than 14% of unsatisfactory river water is due to stormwater runoff in urban areas. The quality of the water drained by permeable and conventional pavements was compared and the results obtained are shown in Table 1. It is possible to perceive that the permeable pavement has great participation in the process of treatment of stormwater, being able to be a great facilitator in the development of sustainable drainage systems.

Table 1. Reduction of pollutants when using permeable pavements compared to conventional pavements.

Parameter	Reduction of Pollutants (%)
Suspended solids	80–99
Phosphorus	65–71
Nitrogen	75–85
Total organic carbon	82
Lead	50–98
Zinc	62–99
Chrome	87–88
Cadmium	0–34
Copper	42
Heavy metals	90–99
Biochemical oxygen demand	80–83
Chemical oxygen demand	88
Hydrocarbons	95
Oil	97–98

Source: Based on James [30].

Gilbert and Clausen [31] evaluated the amount of stormwater drained in two types of sidewalks: one with typical asphalt surface and other covered with paver. Paver driveways were constructed with stone blocks (115 by 230 mm) interlocking concrete permeable pavement. Pavers were hand installed over 5 cm compacted and screeded coarse sand on top of 15 cm processed gravel. Drainage voids comprised 12% of the surface area and were filled with 3–6 mm peastone. The reduction in the runoff from asphalt to the paver was 72%. The mean infiltration was zero for the asphalt and 11.2 cm/h for the paver. However, the rate of infiltration of the paver pavement decreased with time due to pore obstruction by fine particles. The water drained by the paver sidewalk contained significantly less pollutants compared to the asphalt pavement. Considering the benefits in reducing the runoff and the high infiltration rates, the use of paver in the construction of sidewalks over the traditional asphalt material is more advantageous.

Hou et al. [32] evaluated the infiltration rate of three different types of permeable pavement systems compared to a conventional pavement system. For rainfall rates less than 59 mm/h, the runoff coefficient was zero for the permeable pavement, while the conventional pavement coefficient was 0.85. In addition to the better infiltration rate, it was also verified that the runoff start time after the rain event was higher for the permeable pavement (73 min later). Consequently, the discharge time of stormwater was also higher, which reduces the risk of flooding caused by heavy precipitation.

Eck et al. [33] evaluated the use of Permeable Friction Course (PFC) in the states of Texas and North Carolina in the USA. PFC is a layer of porous asphalt laid in thicknesses of 25 to 50 mm overlaying conventional impermeable pavement. PFC is a type of permeable pavement made of coarse and fine aggregates, asphalt binders, and stabilizing additives, but it does not encourage infiltration and reduces flow volume, such as the full depth permeable pavement. Instead, PFC layers remove rainfall from the road surface and allow it to flow through the porous layer to the roadside. With the use of PFC, the total suspended solids had a reduction of up to 96% when compared to conventional pavement, and good results were found for other parameters such as phosphorus (reduction of up to 78%), copper (69%), lead (above 90%) and zinc (90%). The performance of the Permeable Friction Course can be compared to that of a sand filter because the particulate substances are well filtered while the dissolved substances have little or no retention. Regarding the runoff, 29% to 47% of the total precipitation was retained.

2.3. *Application of Stormwater Collected from Permeable Pavements for Non-Potable Uses in Buildings*

As seen in the previous section, permeable pavements have the ability to retain pollutants and improve the quality of stormwater. Some studies have evaluated the possibility of using this water for non-potable uses in buildings, such as toilet flushing, garden watering, car washing, among others.

Pratt [34] performed a case study at a UK-based hostel whose building had 400 m^2 of roof area and 325 m^2 of parking area. Stormwater precipitated on both surfaces would be stored in the parking sub-base. The parking surface contained permeable blocks that allowed infiltration of stormwater into the sub-base. The water stored in the sub-base was connected to a tank in the hostel and used for toilet flushing. The water storage capacity on the pavement was approximately equal to 34 m^3.

Antunes et al. [35] evaluated the possibility of using stormwater from permeable pavements in non-potable uses in residential, commercial and public buildings in the city of Florianópolis, Brazil. In the study, two models of porous asphalt concrete modified with rubber and Styrene-Butadiene-Styrene (SBS) polymer were assessed. The mean percentage of infiltration found for the models was 85%. In this way, the potential for potable water savings ranged from 1 to 18% in the residential sector, 2 to 57% in the public sector, and 6 to 69% in the commercial sector, depending on the tank size.

Hammes et al. [36] evaluated the performance of two permeable pavements in terms of quantity and quality of infiltrated stormwater, aiming at its use in activities that allow the use of non-potable water. The pavements structures are shown in Figure 2 (models A and B). The permeable pavements tested had a mean of 70 and 80% infiltration, respectively. The lower infiltration value for the model A was mainly due to the presence of the filter course. A positive influence of the pavements was observed in some parameters of water quality. However, the need for an additional treatment of the water to adapt it to the expected quality for use was verified. In addition, it was proposed to use the permeable pavement in a parking lot of the Federal University of Santa Catarina (Brazil) for stormwater infiltration, storage and subsequent use in toilets and urinals flushing. The potential for potable water saving would be at least 53%.

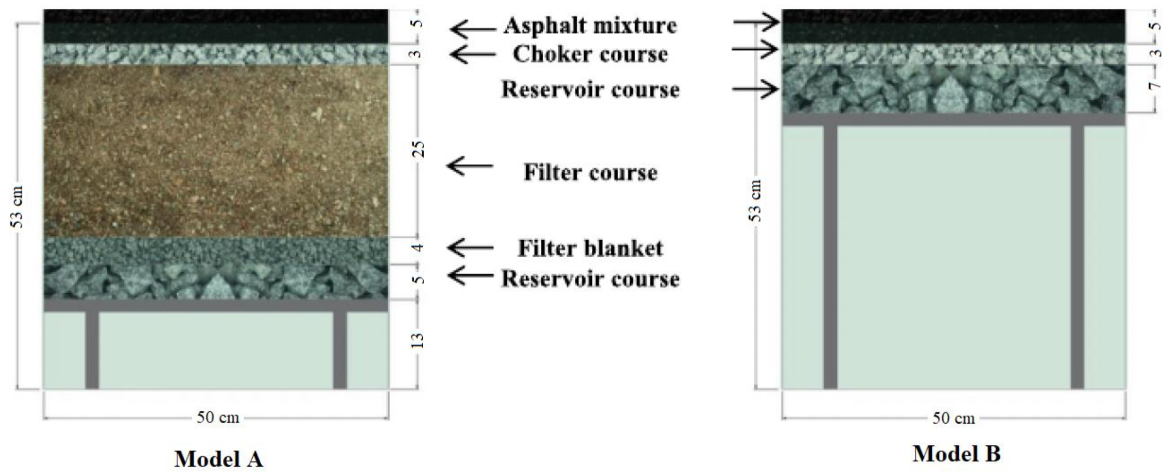

Figure 2. Permeable pavement models tested. **Source:** Hammes et al. [32].

Thives et al. [37] conducted a study to determine the infiltration capacity and the quality of stormwater infiltrated by permeable pavements with drainage asphalt concrete surface. The concentrations of phosphorus, iron, aluminium, zinc, nitrite, chromium, copper and pH increased after the infiltration in the pavements studied, while the ammonia concentration decreased. However, only phosphorus and aluminium concentrations exceeded the limits required for non-potable uses. It was also found that at least 84% of stormwater could be infiltrated and would be available for non-potable uses.

Thives et al. [38] carried out a study to estimate the potential for potable water savings in multifamily buildings using stormwater collected from paved streets in an area of the city centre of Florianópolis, southern Brazil. For a paved area equal to 9058 m^2 and a stormwater tank capacity of 1000 m^3, the potential for potable water savings ranged from 17 to 33% according to the water demand for non-potable purposes.

Although pollutant removal rates vary according to climatic conditions and permeability parameters, the studies mentioned in this review demonstrate the efficiency of permeable pavements in reducing stormwater runoff, as well as improving water quality infiltrated through the pavement. However, the literature still lacks publications related to the real sustainability of permeable pavements, which should relate the benefits brought by these systems to the environmental impacts produced during all phases, from material extraction to the end of the pavement lifespan.

3. Life Cycle Assessment

Awareness regarding the forecasting and prevention of environmental impacts related to construction is increasing. In this way, interest in developing methods to better understand and deal with these impacts has been increasing. One of the techniques in development for this purpose is life cycle assessment (LCA). LCA can identify opportunities for improving the environmental performance of services at various points in their life cycles, as well as selecting relevant environmental performance indicators, assisting decision-makers in governmental or nongovernmental organizations, for example defining priorities and strategic planning [39].

LCA focuses on potential environmental impacts, such as the use of resources and the consequences of releases to the environment throughout the life cycle of a product or service, from the acquisition of raw materials, production, use, post-use treatment, recycling until final disposal. LCA studies are composed of four phases: goal and scope; life cycle inventory; impact assessment; and interpretation [40].

3.1. Pavements Life Cycle Assessment

This section presents a brief literature review about traditional pavements life cycle assessment, showing some of the various studies and giving the reader an overview about the subject. AzariJafari et al. [41] highlight the large increase in the number of studies on the life cycle assessment of conventional pavements. Current literature demonstrates a wide range of environmental load implications associated with pavements [42–44]. Chiu et al. [45] demonstrated that actions aimed at sustainable development in pavement construction projects can lead to the reduction of greenhouse gas emissions and their life cycle cost. However, there are still immature concepts, which require more research in the coming years, in different stages of the evaluation of the pavement life cycle. One of the fields still little explored is that of permeable pavements. Few studies regarding the life cycle of these pavements and the environmental benefits that can be achieved through the retention of water and consequent reduction of the problems related to floods and water recharge are found in the literature.

LCA is an appropriate tool that can help designers deal with the environmental aspects of their pavements to achieve the goal of building more sustainable pavements. In fact, LCA helps to quantify, analyse and compare the environmental impacts of different types of pavement, from material extraction to the end of its lifespan [19].

AzariJafari et al. [41] compared publications involving LCA of several types of pavements. The results show a significant heterogeneity of functional units and other components. LCA standards, such as ISO 14040 and 14044, do not have technical details on, for example, phases and processes that should be included in the assessment, the lifespan to be analysed, or what the minimum amount of data is that should be considered in modelling LCA. In addition to inconsistencies between publications, significant differences in calculated life cycle environmental impact outcomes make comparisons of results simply impossible.

Approximately US$150 billion and 320 million tonnes of building materials are invested annually in the construction, rehabilitation and maintenance of pavements in the United States. However, very little is known about the environmental damages caused by the construction of these pavements [46]. Some studies have shown that the type of pavement can influence vehicle fuel consumption [47,48]. Taylor and Patten [48] have shown that Portland cement-based concrete pavements can decrease the amount of fuel consumed when compared to pavements constructed with hot-mix asphalt concrete (HMA).

Huang et al. [49] developed a life cycle assessment tool for the construction and maintenance of asphalt pavements. The structure of LCA was composed of process parameters (energy consumed in transport, material production and pavement construction), pavement parameters (size, materials used, lifespan), unit, project inventory and characterization results. The results are divided into different categories, such as depletion of minerals and fossil fuels, depletion of the ozone layer, global warming, acidification, photo-oxidant formation, human toxicity, eco-toxicity, eutrophication, among others. The study proposed a method for grouping and weighting categories, according to the "Eco-points" developed by the Building Research Establishment (UK) for the construction sector, as shown in Figure 3.

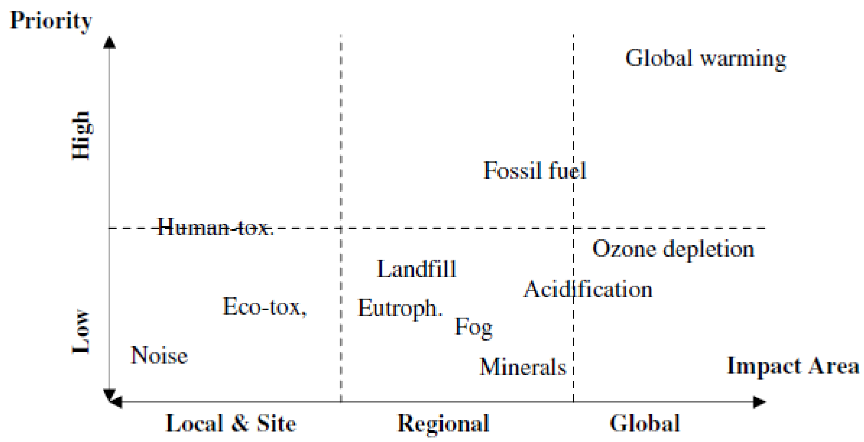

Figure 3. Grouping and weighting of LCA environmental impact categories. **Source:** Huang et al. [49].

Huang et al. [49] used the proposed LCA methodology to conduct a case study investigating the environmental impacts of the asphalt pavement life cycle on a highway, in which the natural aggregates were partially replaced with glass residues and incineration ash. The results were compared to conventional pavement of the same size and function, but using only virgin aggregates. Asphalt mixing, bitumen and aggregates production consumed, respectively, approximately 62%, 23% and 6% of the total energy and consequently produced more emissions than the other processes. The use of recycled materials reduced the consumption of asphalt binder by about 7%. Another significant benefit of recycling was the saving of 5766 tonnes of aggregates and the recycling of 579 and 989 tonnes of glass waste and incineration ash respectively. Aggregate transport accounted for more than 61% of all diesel use, due to the long transport distance (193 km). Trains with higher fuel efficiency (0.17 MJ/t.km) than trucks (0.46–0.94 MJ/t.km) were used to transport aggregates. Glass and ash were obtained from local sources and the use of diesel to transport asphalt was only 17%, as the highway was located very close to the asphalt plant (6.4 km). The results of this study show the great dependence of the location of the road and the materials used in the pavement structure, which significantly interfere with the environmental impacts of the life cycle.

Santero and Horvath [50] evaluated the global warming potential of conventional pavements in the United States, analysing several components such as: extraction and production of materials, transportation, equipment used, carbon absorption, heat islands, surface roughness of the pavement, rolling resistance, albedo, among others. Figure 4 shows the emission of carbon dioxide (in Mg CO_2e) per kilometre of road over 50 years obtained by Santero and Horvath [50]. Grey bars show variations of global warming potential, while black bars show the extreme values of each component. The results demonstrate the wide range of possible impacts to the components of the pavement life cycle. This impact ranges from insignificantly small to 60,000 Mg CO_2e per kilometre of road over 50 years.

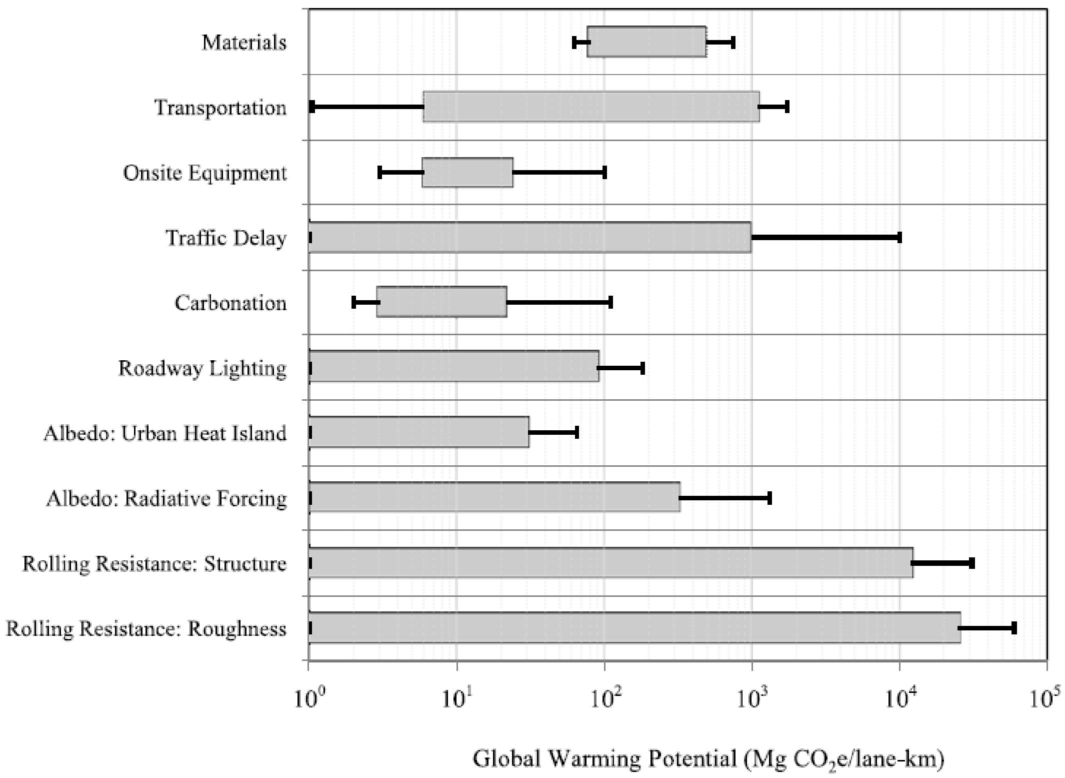

Figure 4. Impact of the global warming potential for components of the pavement life cycle. **Source:** Santero and Horvath [50].

3.2. Permeable Pavements Life Cycle Assessment

In recent years, the use of permeable concrete as paving material in low volume road applications has gained importance due to its positive environmental aspects. Due to the increased use of permeable concrete in the pavement industry, there is large scope for future research to better understand the material, which will make it a promising material for sustainable future roads [51]. Wang et al. [11] developed a model of LCA that can be applied to permeable pavements of both asphalt and concrete in order to evaluate the environmental impacts caused by these types of pavement. The impacts investigated in the study were related to urban floods, stormwater recycling and water purification. The authors compared the use of a permeable asphalt pavement with a conventional asphalt pavement on a typical four-lane secondary highway. The results showed that in 10 km of the modelled highway, 49 TJ of energy consumption, 6700 tonnes of CO_2e emissions, 0.1 tonne of lead emission and 1.0 tonne of zinc emission could be avoided if permeable pavements were used in place of conventional pavement. The study showed that the most significant reduction in energy consumption, greenhouse gas emissions, lead emissions and zinc emissions occurs during the use phase of the pavement. In addition, in an area of 200,000 m^2 (10 km $\times$ 20 m), the volume of stormwater recycled to the subgrade annually using the permeable pavement is 154,000 m^3.

Spatari et al. [13] examined the reduction of energy consumption and the reduction of greenhouse gas emissions through selected Low Impact Development (LID) strategies using the LCA in an urban watershed model. The LID strategies consisted of a retrofit in the conventional sidewalks (with impervious surface), these being replaced with permeable pavements. An annual energy reduction of 7.3 GJ and a 0.4 tonne reduction in greenhouse gas emissions were estimated for the strategy implemented in a neighbourhood of New York City. Examining the materials for the LID strategy, the rubber mats and concrete sidewalk components contribute most to the embodied energy (31% and 28%, respectively) and greenhouse gas (GHG) emissions (34% and 27%, respectively), while transportation energy accounts for approximately 10% of the construction materials' life cycle energy and 17% of life cycle GHG emissions. The annual savings are small compared to the energy intensity and greenhouse gases of LID materials, resulting in slow environmental return (paybacks ranged from 70 to 180 years). This preliminary analysis suggests that if implemented along an urban watershed, LID strategies can have significant energy cost savings for water pollution control facilities, and may advance in reducing their carbon footprint.

A study by the Brazilian Council for Sustainable Construction [52] carried out the evaluation of the modular life cycle of concrete blocks for interlocking pavements, which can be used as surface of permeable pavements. The study estimated indicators such as material use, water and energy consumption, CO_2 emission and waste generation in the production process. The data were collected in 33 block factories, located in different regions of Brazil. The results showed the great variability in the consumption, depending mainly on the type of production adopted by the factories and also on the dimensions of the blocks. Energy consumption ranged from 50 to 810 MJ/m^2. The CO_2 emission varied from 10 to 70 $kgCO_2/m^2$. Water consumption, in turn, varied from 0.01 to 0.91 litres/piece. The waste generated by the factories is diverse, such as wood, plastic, paper, oil, steel and cementitious material. The percentage of recycling practiced by the factories ranges from 67% to 100%.

Li et al. [53] evaluated the life cycle of different sustainable drainage systems: permeable pavements, green roofs and wetlands. Indicators at all stages of the life cycle (construction, operation, maintenance and final disposal) were evaluated. The results showed that the abiotic depletion potential, the acidification potential and the global warming potential of the three drainage systems obtained the greatest impacts in each category: resource depletion, ecosystems and human health, respectively. The impact on human health is related to the concrete used in construction, directly impacting the exhaustion of resources. Resource depletion has also contributed significantly to ecosystem damage, while high abiotic depletion is mainly due to the transport of materials. The study also showed that permeable pavements contributed significantly to flood reduction, with a runoff control rate of 67.5%. However, permeable pavements obtained the highest abiotic depletion potential, mainly due to the greater use of building materials in their structure.

Maiolo et al. [9] developed a methodology based on the sustainability index to evaluate the life cycle of permeable pavements and green roofs implemented in Italy. Figure 5 shows the structure of the permeable pavement used in the study. The application of the LCA highlighted that there are substantial contributions to the layers made up of natural material (sand, gravel), which have an impact due to transportation from the place of origin to the place of execution of the system. In addition, the life cycle of polymeric materials is the same for both drainage systems because of non-renewable sources of energy supply and transport types whose energy class is not particularly competitive. A confirmation of this fact is that the contribution of carbon dioxide has a higher percentage than the emissions of other gases (methane and dinitrogen monoxide), as shown in Figure 6. In conclusion, the authors state that the comparison between the sustainability indices shows that the green infrastructures are technologies that adequately reflect the objective of reducing the environmental impact produced by drainage systems.

A study conducted by the Center for Neighborhood Technology (CNT) and American Rivers [54] showed that air temperature can be reduced by permeable pavements, which absorb less heat than conventional pavements. By reducing the heat island effect in urban areas, such cooling can reduce diseases and fatalities related to excessive heat during extreme events of high temperatures and heat waves.

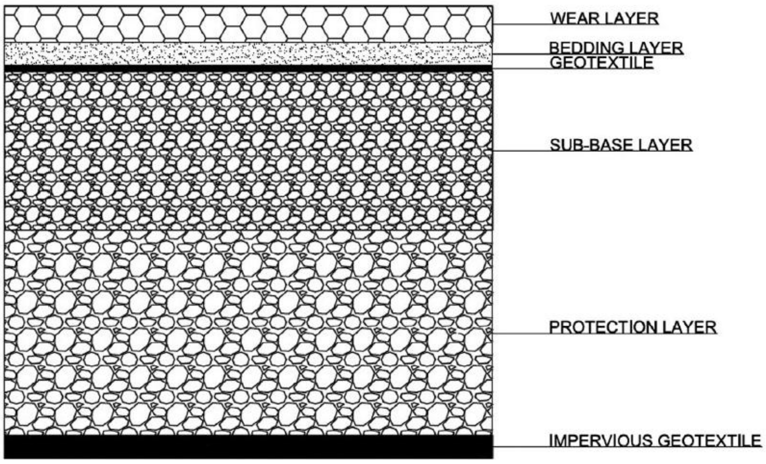

Figure 5. Structure of the permeable pavement used in the study. **Source:** Maiolo et al. [9].

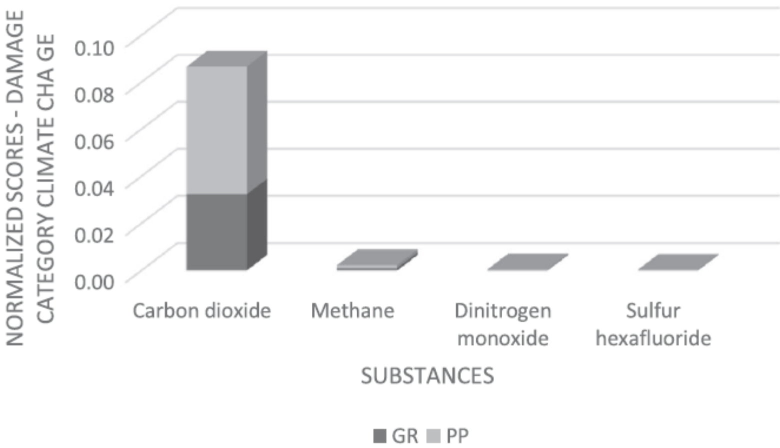

Figure 6. Gases emitted during the life cycle of permeable pavement (PP) and green roof (GR). **Source:** Maiolo et al. [9].

De Sousa et al. [15] compared the life cycle assessment of three different drainage systems in the United States. System 1 consisted of green infrastructures including 27.12 ha of permeable pavements, 1.18 ha of bioretention basins, 2.80 ha of infiltration plants, 1.06 ha of rain gardens and 8.54 ha of cisterns in the subgrade. This combination was collectively sized to capture the first 2.5 cm runoff generated from approximately one-third of the total drainage area. The infrastructure of system 1 occupied about 5% of the total area. Systems 2 and 3 were grey infrastructures. System 2 only retains the runoff in a storage tank and launching it into the Bronx River, while system 3 also performed the treatment prior to launching into the river. The installation of system 1 emitted 20,000 t CO_2e, compared to 31,500 t CO_2e of system 2 and 100,000 t CO_2e of system 3. Of the total emissions associated with the construction of green infrastructures, the major contributions came from transport (8500 t CO_2e), followed by the production of cement and concrete (8400 t CO_2e).

The study also presented a cumulative emission estimate for the phase of operation and maintenance of the systems in a period of 50 years. The net emissions of the green strategy were 19,000 t CO_2e, while grey strategies emitted 85,000 t CO_2e (detention) and 400,000 t CO_2e (detention and treatment). These results were significantly influenced by the emissions associated with the operation and maintenance activities required for systems 2 and 3, and by the sequestration of carbon provided by vegetation in system 1. Thus, it is noted that green infrastructures have a superior environmental performance when compared to grey infrastructure systems.

Yuan et al. [55] compared the environmental and economic impacts of manufacturing permeable paving blocks (with at least 10% porosity) compared to conventional paving blocks in China.

The functional unit used in the study was 1 m^2. All inputs of raw materials, energy consumption, transport, waste and effluent discharge were calculated using the functional unit as a baseline for the two types of block production processes. Only the phase of production of the blocks and the phase of acquisition of the raw materials were considered. The economic cost to produce blocks of conventional pavement and permeable blocks was 24.26 RMB (in October 2018, 1 Chinese Yuan (RMB) is equal to 0.15 United States Dollar (US$)) and 29.68 RMB per m^2, respectively. The results showed that cement was the material that caused the greatest environmental impact on the permeable blocks. This impact could be optimized by reducing consumption. The result of the calculation showed that if cement consumption were reduced by 5%, the overall environmental impact would be reduced by about 2.21%, and the cost of production would be reduced by 1.02 RMB. The coefficient of permeability of the blocks was 1.8×10^{-2} m/s. Thus, during a 3-year service period, the blocks would have a stormwater infiltration capacity of 2.01 m^3 per 1 m^2 of area.

3.3. Life Cycle Cost Analysis

There is little published data on the life cycle cost analysis (LCCA) of permeable pavements that include actual costs and performance. Most studies are limited to comparative initial cost analyses for permeable pavements compared to conventional pavements, which indicates that the cost of permeable pavements is greater than the cost of conventional pavements; however, some studies indicate that the initial total costs are similar or lower because permeable pavements do not require stormwater drainage systems [19].

According to Mei et al. [56], rulers face the increasingly difficult task of planning water management systems in urban areas, especially in relation to uncertainties of climate and socioeconomic changes, which requires decision-makers to plan the water management infrastructure from economic and adaptation points of view. For a specific area, considering draining a region, several green infrastructure options are possible within the scope of planning. However, the systems have different impacts and hydrological costs, making assessments necessary to integrate the sustainability and cost-benefit of these systems.

Wang et al. [19] conducted a life cycle cost analysis to understand the cost implications of building and maintaining permeable pavements. The input data for the models were obtained from laboratory research and computer performance modelling. A detailed life cycle assessment could not be performed due to insufficient available data on the construction, long-term performance, maintenance and salvage value of permeable pavements and alternative Best Management Practices (BMPs) currently used for stormwater management. Two scenarios were considered in the study: a shoulder retrofit of a high-speed highway, and a low-speed highway or parking lot/maintenance yard. Both scenarios compared conventional pavements with conventional treatment BMP versus the use of permeable pavements. The results indicate that permeable pavements are potentially more cost effective than currently available BMP technologies. These results were used to prepare preliminary paving projects for pilot studies of permeable pavement in California and to identify under what conditions they are appropriate for use. Although a more comprehensive life cycle assessment should be undertaken after the completion of the pilot studies.

Kluck et al. [57] point out that, in Holland, pavements with permeable surface are used in order to reduce noise produced by the traffic. However, permeable pavements have a shorter lifespan than traditional pavements, causing frequent maintenance and supposedly increasing costs and thus causing economic and environmental damage. The study conducted by the authors aimed to replace the traditional binder used in the permeable pavement by synthetic binders in order to increase the lifespan of the system. Considering the net present value of the investment, it was concluded that the permeable pavement produced with the synthetic binders costs the same as the conventional pavement, but with a life cycle up to ten times greater, which brings environmental and economic benefits for the drainage system of the Dutch urban areas.

The economic benefits of permeable pavements can be appreciated when life cycle cost analysis is performed. However, due to the lack of large-scale testing, long-term performance data, and construction and maintenance cost data, life cycle cost analysis has been difficult to perform, requiring several assumptions. Wang et al. [19] compared permeable pavement systems with conventional stormwater management systems used at the road shoulders. Permeable pavements reduced life cycle costs by up to 30%. In another study, conducted by Terhell et al. [58], based on data obtained from several agencies, it was found that permeable pavements can save up to US$64,649, considering installation costs, and US$3,788,856 considering stormwater treatment benefits over 25 years for 1/2 acre area compared to conventional pavement. The reduction in the cost of construction is attributed mainly to the fact that permeable pavements do not require side drains, overlays and so on.

To compare flood control efficacy and cost-benefit of green infrastructures, Mei et al. [56] evaluated the implementation of permeable pavements, green roofs, wetlands and bioretention basins in China. The increasing order of effectiveness of flood control was: green roof, permeable pavement, wetland and bioretention basin. This sequence is related both to the characteristics of the study area and to the properties of the specific practices of the green infrastructures. Implementation of the combination of the four practices would result in a peak flow reduction of 80.62%. The study also contemplated the life cycle cost of the systems, considering the phases of design, planning, construction, operation and benefits brought by the strategies. The increasing order of life cycle cost was wetland (US$31.72/$m^2$), permeable pavement (US$98.48/$m^2$), bioretention basin (US$186.90/$m^2$), and green roof (US$317.10/m^2). As a conclusion, it was found that the combination of permeable pavements with bioretention basins and wetlands is recommended as the best strategy for flood control and cost-benefit for the study site.

Chui et al. [59] verified that the life cycle cost of drainage systems depends on the place where they are implemented, and in the case studied, the life cycle cost of the systems were lower in the city of Hong Kong (China) when compared to Seattle (USA). The effective costs for the reduction of runoff were 0.02 L/10^3 US$, 0.15 L/$10^3$ US$, and 0.93 L/$10^3$ US$, for green roof systems, bioretention basin and permeable pavement in the city of Hong Kong, while in the city of Seattle, the figures were 0.03 L/10^3 US$, 0.29 L/$10^3$ US$ and 1.58 L/10^3 US$, respectively. It is noted that the results found by Chui et al. [59] show an opposite cost-benefit order when compared to the study published by Mei et al. [56]. Chui et al. [59] concluded that the relation between the reduction of the stormwater runoff and the cost of the permeable pavement forms an "S" curve; that is, the permeable pavement ideal design tends to have a smaller area and a thinner pavement surface. However, for more intense rainfall events, it is cheaper to expand the surface than to increase depth. The permeable pavement obtained the best cost-benefit for the reduction of the runoff between the three structures studied. Therefore, this type of pavement is recommended for places where stormwater management is the main objective.

3.4. Final Remarks

The review presented in this paper shows that there are several studies whose results prove the sustainability brought by green infrastructures, including permeable pavements, as well as their cost-benefit. However, it can be seen that LCA studies still present a significant heterogeneity of functional units, evaluation limits, phases, processes, parameters and minimum data evaluated, among other components. Thus, the results are often inconsistent, especially when compared to each other, and do not lead to an accurate assessment of the environmental impacts caused by these systems during their life cycles.

4. Conclusions

Due to the increase of impermeable areas and the consequent increase of floods in urban areas, the inadequacy of traditional urban drainage systems is increasingly notable. The trend is that the flood events and other problems related to the recharge and pollution of water resources will grow in the coming years due to global warming and man-made changes. In this way, the importance of using new sustainable drainage systems increases in order to enhance the permeability of surfaces and restore the natural hydrological cycle. These systems include permeable pavements, which were the focus of this paper.

The literature reviewed shows that permeable pavements are capable of filtering and storing stormwater. When compared to the traditional drainage system, they are sustainable and cost efficient, being fully adequate for urban areas, bringing benefits such as reducing stormwater runoff, as well as improving the quality of water infiltrated through the pavement. The LCA studies reviewed were able to provide an estimate of the sustainability of permeable pavements. However, there is still a need for a methodology capable of providing more precise results regarding the environmental impacts caused by these pavements. Thus, the evaluation should not be linked only to environmental benefits related to their lifespan, but assessments are necessary in the steps that precede and follow the lifespan.

Various parameters, such as local weather patterns, regulatory requirements, infiltrated stormwater quality, lifespan and treatment efficiency of systems, should be taken into account. The phases of goal and scope, inventory analysis, impact assessment and interpretation should be more homogeneous, defining phases and processes of the evaluation and the minimum amount of data to be considered in the modelling of LCA. Thus, heterogeneity in the functional units and other components should be avoided, bringing more consistent results and leading to a real evaluation of the environmental impacts caused by permeable pavements.

Although life cycle studies on permeable pavements still present several immature concepts, being only in their early stages, LCA is essential to guide planning and decision-making, leading to systems that consider the increase of water resources and the reduction of natural disasters and environmental impacts.

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References

1. Min, S.K.; Zhang, X.; Zwiers, F.W.; Hegerl, G.C. Human contribution to more-intense precipitation extremes. *Nature* **2011**, *470*, 378–381. [CrossRef] [PubMed]
2. Wasko, C.; Sharma, A. Steeper temporal distribution of rain intensity at higher temperatures within Australian storms. *Nat. Geosci.* **2015**, *8*, 527–529. [CrossRef]
3. Luo, P.; Mu, D.; Xue, H.; Ngo-Duc, T.; Dang-Dinh, K.; Takara, K.; Nover, D.; Schladow, G. Flood inundation assessment for the Hanoi Central Area, Vietnam under historical and extreme rainfall conditions. *Sci. Rep.* **2018**, *8*, 12623. [CrossRef] [PubMed]
4. Brunetti, G.; Simunek, J.; Piro, P. A comprehensive numerical analysis of the hydraulic behavior of a permeable pavement. *J. Hydrol.* **2016**, *540*, 1146–1161. [CrossRef]
5. Scholz, M.; Grabowiecki, P. Review of permeable pavement systems. *Build Environ.* **2007**, *42*, 3830–3836. [CrossRef]
6. Ball, J.E.; Rankin, K. The hydrological performance of a permeable pavement. *Urban Water J.* **2010**, *7*, 79–90. [CrossRef]
7. Pagotto, C.; Legret, M.; Le Cloirec, P. Comparison of the hydraulic behaviour and the quality of highway runoff water according to the type of pavement. *Water Res.* **2000**, *34*, 4446–4454. [CrossRef]
8. Brattebo, B.O.; Booth, D.B. Long-term stormwater quantity and quality performance of permeable pavement systems. *Water Res.* **2003**, *37*, 4369–4376. [CrossRef]
9. Maiolo, M.; Carini, M.; Capano, G.; Piro, P. Synthetic sustainability index (SSI) based on life cycle assessment approach of low impact development in the Mediterranean area. *Cogent Eng.* **2017**, *4*, 1410272. [CrossRef]

10. Glick, S.; Shuler, S.; Guggemos, A.A. Life cycle analysis for sustainable development: A case study of parking lot pavements. *Int. J. Construct. Educ. Res.* **2013**, *9*, 226–236. [CrossRef]
11. Wang, Y.; Li, H.; Ghadimi, B.; Abdelhady, A.; Harvey, J. Initial evaluation methodology and case studies for life cycle impact of permeability of permeable pavements. *Int. J. Transp. Sci. Technol.* **2018**, *7*, 169–178. [CrossRef]
12. Electric Power Research Institute. *Water & Sustainability: U.S. electricity consumption for water supply & treatment e the next half century, 4, Topical Report*; Electric Power Research Institute: Palo Alto, CA, USA, 2002.
13. Spatari, S.; Yu, Z.; Montalto, F.A. Life cycle implications of urban green infrastructure. *Environ. Pollut.* **2011**, *159*, 2174–2179. [CrossRef] [PubMed]
14. City of New York. *PlaNYC Sustainable Stormwater Management Plan 2008*; City of New York: New York, NY, USA, 2008.
15. De Sousa, M.R.C.; Montalto, F.; Spatari, S. Using life cycle assessment to evaluate green and grey combined sewer overflow control strategies. *J. Ind. Ecol.* **2012**, *16*, 901–913. [CrossRef]
16. Ghimire, S.R.; Johnston, J.M.; Ingwersen, W.W.; Sojka, S. Life cycle assessment of a commercial rainwater harvesting system compared with a municipal water supply system. *J. Clean. Prod.* **2017**, *151*, 74–86. [CrossRef] [PubMed]
17. Mullaney, J.; Lucke, T. Practical review of pervious pavement designs. *Clean. Soil Air Water* **2014**, *42*, 111–124. [CrossRef]
18. Associação Brasileira de Normas Técnicas (ABNT). *NBR 16416/2015: Pavimentos Permeáveis de Concreto—Requisitos e Procedimentos (NBR 16416/2015: Pervious Concrete Pavement—Requirements and Procedures)*; Associação Brasileira de Normas Técnicas (Brazilian Association of Technical Standards) (ABNT): São Paulo, Brazil, 2015.
19. Wang, T.; Harvey, J.T.; Jones, D. *A Framework for Life-Cycle Cost Analyses and Environmental Life-Cycle Assessments for Fully Permeable Pavements*; Technical Memorandum, Institute of Transportation Studies, Caltrans Document No.: CTSW-TM-09-249.03 UCPRC Document No.: UCPRC-TM-2010-05; Institute of Transportation Studies: Davis, CA, USA, 2010.
20. Beecham, S.; Lucke, T.; Myers, B. Designing porous and permeable pavements for stormwater harvesting and reuse. In Proceedings of the First European IAHR Congress, International Association for Hydro-Environment Engineering and Research, Edinburgh, UK, 4–6 May 2010.
21. Jia, H.; Lu, Y.; Yu, S.L.; Shen, Y. Planning of LID–BMPs for urban runoff control: The case of Beijing Olympic Village. *Sep. Purif. Technol.* **2012**, *84*, 112–119. [CrossRef]
22. Sansalone, J.; Kuang, X.; Ying, G.; Ranieri, V. Filtration and clogging of permeable pavement loaded by urban drainage. *Water Res.* **2012**, *46*, 6763–6774. [CrossRef] [PubMed]
23. Park, D.G.; Sandoval, N.; Lin, W.; Kim, H.; Cho, Y.H. A case study: Evaluation of water storage capacity in permeable block pavement. *KSCE J. Civ. Eng.* **2014**, *18*, 514–520. [CrossRef]
24. Knappenberger, T.; Jayakaran, A.D.; Stark, J.D.; Hinman, C.H. Monitoring porous asphalt stormwater infiltration and outflow. *J. Irrig Drain Eng.* **2017**, *143*, 04017027. [CrossRef]
25. Pratt, C.J.; Mantle, J.D.G.; Schofield, P.A. UK research into the performance of permeable pavement, reservoir structures in controlling stormwater discharge quantity and quality. *Water Sci. Technol.* **1995**, *32*, 63–69. [CrossRef]
26. Pratt, C.J.; Mantle, J.D.G.; Schofield, P.A. Urban stormwater reduction and quality improvement through stormwater reduction and quality improvement through the use of permeable pavements. *Water Sci. Technol.* **1989**, *21*, 769–778. [CrossRef]
27. Ramsey-Washington Metro Watershed District. Porous Asphalt Parking Lot. Little Canada, 2006. Available online: http://rwmetrowatershed.govoffice.com/vertical/Sites/%7BAB493DE7-F6CB-4A58-AFE0-56D80D38CD24%7D/uploads/%7B495C857D-FED3-409E-B58A-E6A16D827DEA%7D.PDF (accessed on 12 July 2018).
28. Legret, M.; Colandini, V. Effects of a porous pavement with reservoir structure on runoff water: Water quality and fate of heavy metals. *Water Sci. Technol.* **1999**, *39*, 111–117. [CrossRef]
29. Pratt, C.J.; Newman, A.P.; Bond, P.C. Mineral oil bio-degradation within a permeable pavement: Long term observations. *Water Sci. Technol.* **1999**, *39*, 103–109. [CrossRef]
30. James, E. A Literature Review on the Effect of Porous Asphalt Roads on Water Pollution. In *Sustainable Road Surfaces for Traffic Noise Control*; Silvia Project Report; European Commission: Ottawa, ON, Canada, 2013.

31. Gilbert, J.K.; Clausen, J.C. Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. *Water Res.* **2006**, *40*, 826–832. [CrossRef] [PubMed]
32. Hou, L.; Feng, S.; Ding, Y.; Zhang, S.; Huo, Z. Experimental study on rainfall-runoff relation for porous pavement. *Hydrol. Res.* **2008**, *39*, 181–190. [CrossRef]
33. Eck, B.J.; Winston, R.J.; Hunt, W.F.; Barrett, M.E. Water Quality of Drainage from Permeable Friction Course. *J. Environ. Eng.* **2012**, *138*, 174–181. [CrossRef]
34. Pratt, C.J. Use of permeable, reservoir pavement constructions for stormwater treatment and storage for re-use. *Water Sci. Technol.* **1999**, *39*, 145–151. [CrossRef]
35. Antunes, L.N.; Thives, L.P.; Ghisi, E. Potential for potable water savings in buildings by using stormwater harvested from porous pavements. *Water* **2016**, *8*, 110. [CrossRef]
36. Hammes, G.; Thives, L.P.; Ghisi, E. Application of stormwater collected from porous asphalt pavements for non-potable uses in buildings. *J. Environ. Manag.* **2018**, *222*, 338–347. [CrossRef] [PubMed]
37. Thives, L.P.; Ghisi, E.; Brecht, D.G.; Pires, D.M. Filtering capability of porous asphalt pavements. *Water* **2018**, *10*, 206. [CrossRef]
38. Thives, L.P.; Ghisi, E.; Silva, N.M. Potable water savings in multifamily buildings using stormwater runoff from impermeable paved streets. *Eur. J. Sustain. Dev.* **2018**, *7*, 120–130.
39. Guinée, J.B.; Heijungs, R.; Huppes, G. Life cycle assessment: Past, present, and future. *Environ. Sci. Technol.* **2011**, *45*, 90–96. [CrossRef] [PubMed]
40. International Organization for Standardization (ISO). *ISO 14040/2006: Environmental Management—Life-Cycle Assessment—Principles and Framework*; International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
41. AzariJafari, H.; Yahia, A.; Amor, M.B. Life cycle assessment of pavements: Reviewing research challenges and opportunities. *J. Clean. Prod.* **2016**, *112*, 2187–2197. [CrossRef]
42. Praticò, F.G.; Ammendola, R.; Moro, A. Factors affecting the environmental impact of pavement wear. *Transp. Res. Part D-Transp. Environ.* **2010**, *15*, 127–133. [CrossRef]
43. Santero, N.J.; Masanet, E.; Horvath, A. Life-cycle assessment of pavements. Part I: Critical review. *Resour. Conserv. Recycl.* **2010**, *55*, 801–809. [CrossRef]
44. Giustozzi, F.; Crispino, M.; Flintsch, G. Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability. *Int. J. LCA* **2012**, *17*, 409–419. [CrossRef]
45. Chiu, C.T.; Hsu, T.H.; Yang, W.F. Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resour. Conserv. Recycl.* **2008**, *52*, 545–556. [CrossRef]
46. Holtz, K.; Eighmy, T.T. Scanning European advances in the use of recycled materials in highway construction. *Public Roads* **2000**, *64*, 34–40.
47. Santos, J.; Ferreira, A.; Flintsch, G. A life cycle assessment model for pavement management: Road pavement construction and management in Portugal. *Int. J. Pavement Eng.* **2014**, *16*, 315–336. [CrossRef]
48. Taylor, G.; Patten, J. *Effects of Pavement Structure on Vehicle Fuel Consumption*; Centre for Surface Transportation Technology (CSTT): New Delhi, India; National Research Council of Canada (NRC): Ottawa, ON, Canada, 2002.
49. Huang, Y.; Bird, R.; Heidrich, O. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements. *J. Clean. Prod.* **2009**, *17*, 283–296. [CrossRef]
50. Santero, N.J.; Horvath, A. Global warming potential of pavements. *Environ. Res. Lett.* **2009**, *4*, 034011. [CrossRef]
51. Chandrappa, A.K.; Biligiri, K.P. Pervious concrete as a sustainable pavement material—Research findings and future prospects: A state-of-the-art review. *Constr. Build. Mater.* **2016**, *111*, 262–274. [CrossRef]
52. Conselho Brasileiro de Construção Sustentável (CBCS). *Sustentabilidade na Indústria de Blocos e Pavimento de Concreto: Avaliação do ciclo de vida Modular (Sustainability in the Concrete Block and Pavement Industry: Modular Life Cycle Assessment)*; Conselho Brasileiro de Construção Sustentável (Brazilian Council for Sustainable Construction) (CBCS): São Paulo, Brazil, 2014.
53. Li, Y.; Huang, Y.; Quanliang, Y.; Zhang, W.; Meng, F.; Zhang, S. Multi-objective optimization integrated with life cycle assessment for rainwater harvesting systems. *J, Hydrol.* **2018**, *558*, 659–666. [CrossRef]
54. Center for Neighborhood Technology (CNT); American Rivers. *The Value of Green Infrastructure, a Guide to Recognizing Its Economic, Environmental and Social Benefits*; CNT: Chicago, IL, USA, 2010.

55. Yuan, X.; Tang, Y.; Li, Y.; Wang, Q.; Zuo, J. Environmental and economic impacts assessment of concrete pavement brick and permeable brick production process—A case study in China. *J. Clean. Prod.* **2018**, *171*, 198–208. [CrossRef]
56. Mei, C.; Liu, J.; Wang, H.; Yang, Z.; Ding, X.; Shao, W. Integrated assessments of green infrastructure for flood mitigation to support robust decision-making for sponge city construction in an urbanized watershed. *Sci. Total Environ.* **2018**, *639*, 1394–1407. [CrossRef] [PubMed]
57. Kluck, E.; Ven, M.V.; Baggen, J.; Wee, B.V.; Hofman, R. Environmental life cycle cost for durable porous surface layers with synthetic binders. *Int. J. Pavement Eng.* **2010**, *3*, 142–148.
58. Terhell, S.L.; Cai, K.; Chiu, D.; Murphy, J. *Cost and Benefit Analysis of Permeable Pavements in Water Sustainability*; University of California Agriculture and Natural Resources: Davis, CA, USA, 2015.
59. Chui, T.F.M.; Liu, X.; Zhan, W. Assessing cost-effectiveness of specific LID practice designs in response to large storm events. *J. Hydrol.* **2016**, *533*, 353–364. [CrossRef]