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Exploring the Potential in LID Technologies for Remediating Heavy Metals in Carwash Wastewater

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Abstract: Carwash wastewater (CWW) can be a significant source of environmental pollution due to the diversity and high concentrations of contaminants it contains. This toxic wastewater can contain several different heavy metals that if left untreated, can enter surface and sub-surface waters. Innovative, nature-based solutions such as low-impact development (LID) technologies may provide an eco-friendly CWW treatment process that is both effective and affordable. This research reviews the available literature to provide definitive values of flowrate and contaminant concentrations found in CWW around the globe. Dividing LID technologies into two groups, vegetated and unvegetated systems, the authors explored the literature for the general performance of these technologies to sustainably treat heavy metals in CWW. Depending on the car wash's size and intended purpose, whether cleaning vehicles in agriculture-based rural communities, mining, or in high-density urban environments, volumetric flowrates requiring treatment found in six different countries ranged from 35–400 L/car. CWW also contains a wide range of contaminants at various levels, including COD, turbidity, TDS and TSS, surfactants, oils and greases, and heavy metals such as lead, cadmium, zinc, copper, chromium, and iron. Heavy metal removal by both vegetated and unvegetated LIDs shows mixed results in the literature, but given the different processes involved in both types, the authors propose a system that combines these types in order to provide all the necessary removal processes, including mechanical filtration, adsorption, sedimentation, chemical and biological treatment processes.

Keywords: carwash wastewater; heavy metals; low-impact development; water quality remediation; sedimentation; chemical adsorption; infiltration; bioretention; phytoremediation; rural and remote water management

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Citation: Talebzadeh, M.; Valeo, C.; Gupta, R.; Constabel, C.P. Exploring the Potential in LID Technologies for Remediating Heavy Metals in Carwash Wastewater. *Sustainability* **2021**, *13*, 8727. https://doi.org/10.3390/su13168727

Academic Editor: Chunjiang An

Received: 2 July 2021
Accepted: 3 August 2021
Published: 5 August 2021

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

1. Introduction

Vehicles are not generally given consideration when addressing a region's wastewater generation. However, in addition to air pollution, vehicles can contribute significant amounts of contamination to the environment in the form of a liquid wastewater stream. Wastewater pollutants vary by the activity that generates the wastewater stream. Municipal and industrial wastewater, stormwater runoff, and agricultural wastewater streams all vary in the daily volumes generated, contaminants present and concentrations. These variations largely depend on the intended level of service generating the wastewater stream, its physical size, and its geographical location [1]. Of the wide variety of contaminants known to reside in these wastewater streams, one contaminant that is of concern for many regulated regions is the chemical group referred to as heavy metals [2]. These pollutants can pose serious concerns to the natural environment and human health, even at low levels of exposure [3].

Studies carried out around the world have demonstrated that car-related industries including servicing, maintenance, manufacturing, and washing are recognized as high emitters of air, soil, and water pollution [4]. Vehicles can contribute to wastewater generated in municipalities (residential car-washing facilities), industrial and agricultural activities (vehicles used in these sectors need to be washed at regular intervals as part of their required maintenance), and stormwater runoff (individuals washing their vehicles in driveways flowing into the minor stormwater drainage system as well as rainwater wash-off of impervious surfaces) [5]. Due to the degradation of the vehicle [6] as well as what the vehicle picks up in the environment in which it is functioning, these wastewater streams can include a myriad of contaminants and a suite of heavy metals [7].

Since the carwash industry is expected to grow with increasing urbanization, environmental concerns of the effects of discharging carwash wastewater have received greater attention recently [8]. Contaminated water released from carwash centers in particular may eventually end up in the surface water and groundwater aquifer systems and result in severe damage to aquatic ecosystems if left untreated [6]. Wastewater from vehicle-washing facilities (henceforth referred to as carwash wastewater, CWW) offer a wide range of contaminants including heavy metals; sand and dust; detergents; surfactants; phosphates; grease; waxes; hydrofluoric acid; petroleum hydrocarbon wastes such as motor oil, diesel and petrol [4–7]; and unacceptable levels of acidity and turbidity [9]. In many regions, carwash facilities are fully or partially open-ended buildings that are easily accessible from the roadway, and are either automated or manually operated [10]. In regions where wastewater generation is regulated, CWW cannot be directly discharged from carwash facilities to the urban sewage system before an acceptable level of pre-treatment such as filtration is administered [6,7,11].

The average rate of generated CWW volumes can vary by region; within a region depending on the location, automation level, and the size and operation mode of the vehicle (residential cars vs. large industrial use vehicles); and seasonally as well as daily [1]. This wastewater can pose a challenge for cost-effective treatment, but conversely, may have great potential for graywater recycling and reuse opportunities [12]. Although several studies have been conducted on carwash wastewater reclamation and membrane technologies [5], the implementation and operation cost is very high, especially in the developing world, because membranes are rarely produced there [13]. Where rural and remote operations in possibly impoverished regions generate CWW, innovations are needed for cost-effective but sustainable solutions for treating CWW to a level that makes them compliant with World Health Organization standards, and potentially to a level that provides for water reuse. These innovations must be sustainable, which suggests that the method is not only cost-effective and easily accessible for remote, impoverished regions but environmentally friendly as well. It is known that CWW treatment at the source is not only easier, but is also more cost-effective and more efficient [14]. To be sustainable for these communities, the method must treat the CWW right at the source, use native materials, treat the wastewater in a green or eco-friendly manner, have little-to-no energy use, and be potentially nature-based [15]. Innovative methods for treating contaminated wastewater that fit these criteria are seen in the literature and include wetland treatment systems [16] and low-impact development (LID) technologies [17–19].

LIDs are technologies that provide effective solutions for sustainable stormwater management and treatment because they treat the contaminated water at the source, use native materials, work by gravity drainage with no energy input, uses nature-based solutions for remediation, and recreate the landscape's original permeability prior to urbanization [20]. They treat stormwater quantities by retaining water, holding it in storage, and allowing it to filtrate through a system that delays outflow and works to remove various contaminants in the inflow. Typical examples are rain gardens (also known as bioretention cells), green roofs, grassy swales, and permeable pavement systems [21]. The latter are an unvegetated LID with a highly porous engineered material that allows stormwater to infiltrate in the subsurface where it is retained and filtrated. Unlike wetland-based technologies that are very expansive in surface area, these technologies are intended to work at a much smaller scale than wetlands or conventional stormwater retention ponds [22] found in many urban areas. LIDs are becoming a more prevalent technology in many municipalities with the hope of eventually replacing typical minor and major drainage systems involving underground piped infrastructure.

The disadvantages of LID systems vary depending on the type of LID, location, design, and climate. Vegetated LID systems are living structures that are engineered primarily to treat stormwater quantity rather than quality [23] primarily because the knowledge leading to effective designs for water quantity treatment is far more established than that behind water quality treatment [24]. Once constructed, vegetated LIDs require a maturation wait period before use [25] and phosphorus and nitrogen leaching is possible as vegetation becomes established [26]. Changes in drainage qualities over time due to particle loading [26], clogging of structural components (such as valved drainage lines), and weeding leads to maintenance costs [27] for material replacement and annual [27] or bi-annual inspections [28]. Some sources go so far as to suggest monitoring with specialized equipment [29]. In general, barriers to widespread adoption of vegetated LIDS include uncertainty around costs, long- and short-term maintenance requirements, lack of consistent performance [30], lack of understanding and knowledge leading to effective design, and a lack of trust from the community for this unconventional infrastructure [24].

Permeable pavements such as porous asphalt and porous concrete are generally proprietary blends that provide high porosity and therefore, high infiltration capacity at the surface; but often at the expense of material strength and surface resiliency. The low compressive strengths of porous concrete can unravel and require replacement if placed in high-traffic areas where there is high acceleration and deceleration [31]. Both of these types of pavements as well as the third most common type, interlocking pavers, are known to clog relatively quickly with particulate matter [32]. They require continual maintenance to restore surface infiltration capacities to original levels [31].

Tools for estimating capital and operating costs of LIDs per square meter are readily available on the Internet. In general, capital costs (excluding necessary permits and local requirements) for vegetated LIDs arise from (i) removal of existing vegetation and topsoil; (ii) excavation, grading, hauling, and any other protective devices associated with these and (i); (iii) structural components such as underdrain, valves, liners, pipe geotextiles, etc.; (iv) vegetation, soil, mulch, and potentially sod; (v) any monitoring equipment to be installed during construction; and (vi) labor [28,33]. Operating costs for vegetated LIDs can include labor, material and hauling costs associated with debris removal, weed control, vegetation and soil replacement, and inspections that are recommended at regular intervals as deemed necessary depending on the location [27,34]. Costs for implementing bioretention cells (rain gardens) can be found to vary from USD 30/m^2 to USD 165/m^2 depending on the jurisdiction [27,33,35], with vegetation being the most significant portion of this LID's cost [35]. Permeable paver cost numbers are seen to range from USD 5.50/m^2 to USD 430/m^2 [36]. Porous asphalt cost numbers range from USD 108/m^2 to USD 161/m^2, including installation [36], or USD 10/m^2 to USD 32/m^2 without installation [35], demonstrating that labor makes up most of the cost [36]. Pervious concrete costs are quoted as USD 48/m^2 to USD 195/m^2, noting that this material is roughly 10–20% more expensive on average than regular concrete [36]. Since all of these estimates are dependent on the jurisdiction, economy and date, the most informative way to understand the true cost of LIDs is to compare their cost with the conventional stormwater infrastructure for the same jurisdiction, economy and date. Then and only then can the cost benefits of LIDs become known and potentially affect decision making in the long term for a municipality wishing to use this technology [35].

Yet despite all these disadvantages and costs, LIDs continue to be the stormwater management infrastructure of choice in many regions around the globe. They are sustainable forms of infrastructure than can help communities reach environmentally progressive goals as either a partial or complete replacement of conventional infrastructure for stormwater quantity and quality treatment [20]. Hence, they could potentially be a sustainable solution for carwash wastewater treatment in rural, remote, and impoverished areas. To the authors' knowledge, there is no systematic evaluation or exploration of how the range of LID technologies can be used for treating heavy metals in carwash wastewater. This paper has two objectives: (1) to assess the literature for definitive quantities of possible CWW daily flowrate generation volumes, contaminants present, and concentrations observed in carwash facilities around the world in both urban and rural communities, and (2) to assess the potential for LID technologies to provide sustainable treatment of heavy metals in CWW in rural, remote, and impoverished regions. To achieve objective (1), the literature was reviewed by searching Google Scholar, Science citation index, and Engineering Village. These search engines led to relevant articles using keywords such as wastewater treatment, carwash wastewater, low-impact development, filtration, bioretention, heavy metals, and bioretention effects on wastewater treatment. Abstracts, methods, and results were checked in each paper and were refined to create the database of papers cited in this research. Zotero (https://www.zotero.org/, accessed on 4 January 2021) was used to organize the database and citations. The Authors compiled and summarized all documented information on carwash effluent flowrates and associated contaminants from these studies and the results are presented in Section 2. Knowledge on LID function and capacity for heavy metal remediation of CWW was assessed from the literature and these results are given in Section 3. That section also describes the potential for LIDs to treat heavy metals in CWW given the range of influent flowrates and concentrations. This is followed by a discussion and conclusions. The paper synthesizes all the reports and papers on contamination in carwashes that were accessible to the authors. This review exists nowhere else in this assembled form in the literature and was necessary in order to explore, in general terms, the potential of LIDs to reclaim this potential resource free of heavy metal contamination. Although very little work has been done in this area, and many of the sources were difficult to access, the synopsis that follows is a synthesized summary of what is accessible to the public in the technical and non-technical literature.

2. Carwash Wastewater: A Global Perspective

2.1. Wastewater Volumes Generated at Carwash Facilities

There are generally two types of carwash facilities—automatic and self-serve, with each generating different volumes of water used per vehicle each time a vehicle is washed. Water losses at carwash stations involve evaporation and what is referred to as carry-out. Evaporation losses are simply water that evaporates during the washing process or leaves as a mist. Carry-out water is the amount of used water that remains on the surface or other parts of the vehicle as it leaves the station. A carwash station in Geelong, Australia, reported that 200 L/car of water was used in this automatic carwash facility in an urban area (residential car), and the volume used in the self-serve carwash was lower than the automatic carwash station. This translates into approximately 10,000 L of wastewater generated per day and 3.5 million L per year [37]. These amounts will also differ if the facility is intended for larger vehicles such as those used in agricultural activities, for example. Washing a large vehicle often involves high-pressure washing with flow rates up to 20 L per minute, which would be almost 100 L of water for each large vehicle, in contrast to the 70 L volume used for a standard car [11].

In India, a carwash station located on a university campus washed on average five to seven cars per day, and the total water consumption was estimated to be 200–250 L per day at this particular carwash site (suggesting roughly 35 to 40 L/car) [8]. Another carwash service station located in Mehat, India, reported that an average of 20 cars per day are washed in this center, with water consumption rates of 750–1000 L daily [8], suggesting roughly 40–50 L/car are used. In Pakistan and Malaysia, an average of 40–100 L of water are used for washing a standard car at a carwash station [5,38]. In the USA, a study was done on behalf of the ICA (International Carwash Association) to evaluate and provide a current look at water consumption, evaporation, and carry-out in a professional carwash site. On average, to wash a vehicle in a carwash in the USA, 170 L of fresh water are needed, and 21% of this amount is not returned to the sewer or treatment system due to evaporation and carry-out [39]. The study also noted that the average water consumption in a carwash center is 100 L per car and at least 10,000 L of carwash wastewater are generated in a carwash station daily [39]. Table 1 summarizes the water usage rates at carwash stations, per car, in each country found in the literature.

Table 1. The amount of used water in carwash centers for a standard car.

Location	Used Water (L/car)
India	35–40, 40–50 [8]
Pakistan	100 [5]
Malaysia	40–120 [38]
USA	170 [39]
Australia	200 [37]
Kuwait	200–400 [4]

Table 1 shows that USA, Australia, and Kuwait have much higher rates of water usage than the other countries on the list. The USA is not typically viewed as a water-scarce nation, yet some regions of Australia may be considered water scarce and Kuwait is a very arid region. All the nations listed vary geographically, economically, and socially and there is a 10-fold difference across only these six countries. Thus, it is likely that in developed and developing nations, CWW generation rates can vary by an order of magnitude in liters per car, and depending on the size of the facility in terms of number of cars per day or size of the vehicle, which can result in close to 10 million L of CWW generated annually. Assuming a 20% loss due to evaporation and carry-out, this still presents an enormous resource if recycled and reused properly.

2.2. CWW Contaminant Characteristics

2.2.1. Pollutants Other than Heavy Metals

Only a handful of research studies have been conducted on carwash wastewater characteristics. It is reported that the highest amount of water pollution in a carwash is in the form of chemical oxygen demand (COD), which usually exceeds limits and standards defined by governing bodies [40]. Table 2 provides the amounts and varieties of contaminants (excluding heavy metals) that have been determined from CWW samples. The table also includes the US Environmental Protection Agency's (EPA) maximum permissible limits for industrial wastewater (unless otherwise indicated) as well as the World Health Organization (WHO) standards for drinking water for comparison. Malaysia has established itself as unique in terms of carwash wastewater, as it has maximum permissible limits on CWW within the Environmental Quality Act of 1974 (EQA) for a handful of important parameters [14]. These are also included in Table 2.

Table 2 demonstrates the characteristics and limitations of a typical carwash effluent. Generally, carwash cleaning products contain high amounts of detergents and alkaline liquids, but in recent years, carwash centers have increased the amounts and types of chemicals and surfactant compounds used in their detergents. This has resulted in significantly greater amounts of pollution being generated from vehicle cleaning [41]. As Table 2 shows, in some cases, turbidity and COD were higher than the permissible limits and DO was much lower than the minimum permissible limit in the EQA. The TSS levels for [41] exceeded the USEPA freshwater limit, which is not surprising. However, pH was in the standard range for all studies. Although the characteristics of carwash wastewater are very similar around the world, there are some differences due to the source of carwash wastewater and type of vehicle. For example, in the study conducted in India [8], the amount of turbidity in the carwash wastewater was greater than, and the COD level less than, those found in a study conducted in Malaysia [14]. The presence of mud, sand, brake particles, and dirt result in high values of turbidity in CWW that are washed off of the cars. This increase in turbidity in wastewater means that the carwash wastewater has high amounts of TSS. The presence of detergents is the primary reason for the high COD levels found in CWW, which is the direct result of the oxidation process of organic compounds [7].

Table 2. Parameter concentrations and limits observed in CWW (excluding heavy metals).

Parameter	Concentrations	EPA	WHO	EQA
pH	6.51–8.74 [40] 6.96 [14]	6–9	6.5–8 [42]	6–9
BOD_5 (mg/L)	10.5–11.5 [40] 27–650 [14]	20	<5 [42]	
COD (mg/L)	75–738 [40] 220 [14]	50	N/A	<50
Turbidity (NTU)	34.7–86 [40] 275.1 [14] 109–4000 [14]		<1 [43]	<5
Electrical conductivity (EC) (µS/cm)	150.7–260.7 [40] 62.5 [14]		400 [44]	
Total dissolved solids (TDS) (mg/L)	89.2–151.8 [40] 362–686 [14]		300 [45]	
Dissolved oxygen (DO) (mg/L)	2.55 [14] 0.1 [14]			>7
Surfactants (mg/L)	9.20 [41]			
Total phosphorus (TP) (mg/L)	0.17 [41]	0.1 *		
Total suspended solids (TSS) (mg/L)	114.67 [41]	40 *		
Oils and grease (mg/L)	12–43 [14]			
Petroleum, hydrocarbons, gasoline mg/L	5–24 [14]			
Ammonium (mg/L)	0.4–75 [14]			
Heterotrophic bacteria (CFU/100 mL)	2800–4600 [14]			

* USEPA limits for freshwater.

CWW is also known to contain heavy metals, oil and grease, and unacceptable levels of acidity or alkalinity, polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs). Interestingly, the Authors could only find one study that conducted an analysis of oils and greases in a toxicological, physicochemical, and microbiological analysis of CWW [14]. The results (see Table 2) also revealed excessive bacteria concentrations likely arising through the vehicle's passage through fecal contamination. The Authors of that study noted that the heterotrophic bacteria found was 57% related to the *Aeromonas* species and 43% was closely related to the *Pseudomonas* species [46]. This would be common perhaps for vehicles in rural settings or used in agricultural activities.

2.2.2. Heavy Metal Pollutants

Determining heavy metal contaminants is not a trivial exercise and can be expensive. To the authors' knowledge, only two studies tested and provided observations of heavy metal concentrations in CWW [1,46]. Table 3 shows the observed values determined from the literature, as well as the maximum permissible concentrations of common heavy metals by the WHO for the environment as well as the US EPA maximum permissible limits for surface waters.

In addition, heavy metals take the form of dissolved solids in wastewater streams and when not directly measured. Thus, parameters such as TDS and EC can suggest qualitative estimates of the levels of heavy metal ions (as well as any other ions) in the wastewater stream. Table 2 shows that in both studies that examined these parameters, TDS was higher than the WHO limit, but EC was lower than the WHO limit.

Table 3. Heavy metal concentrations in the environment (WHO) and surface waters (EPA).

Heavy Metal	Concentration	WHO (mg/L) [47]	EPA (mg/L) [42]
Lead	<1 mg/L [46] 0.28 mg/L [1]	0.01	0.05
Copper	0.94–3.8 mg/L [46] 0.06 mg/L [1]	2.0	0.1
Zinc	1.15–3 mg/L [46] 0.18 mg/L [1]	3.0	1.0
Iron	4.97 mg/L [1]	0.3	-
Cadmium	<0.002 mg/L [1]	0.003	0.005
Chromium	0.42 mg/L [1]		
Cobalt	<1 mg/L [46]		

A major source of heavy metal pollution in urban areas are anthropogenic sources such as emissions from road traffic and carwash wastewater [8,37]. Non-exhaust vehicular emissions that result in street dust include brake parts, clutch, tire, and road surface wear. It is reported in various studies that chemical elements such as cadmium, nickel, copper, mercury, and lead ions are the most critical heavy metal contaminants resulting from the increasing use of vehicles. Heavy metals can enter a carwash's wastewater stream by washing off different parts of the car and road dust that has adhered to the vehicles' surfaces. Cadmium, nickel, and lead could be washed off from brake parts, and other heavy metals such as iron, copper, and zinc could be released to the carwash wastewater not only from dust [48,49] attached to the car, but also from different parts of the vehicles [38,47,50]. If these heavy metals remain untreated and enter the environment, they pose a significant threat to human and ecosystem health. One of the most highly toxic heavy metals is cadmium, which has recently become widespread in the environment and is particularly harmful to both the environment and human health [51–53]. Moreover, heavy metal bioaccumulation and biomagnification across aquatic and terrestrial ecosystems have to be considered as a risk to both human and environmental health [54,55]. Since heavy metals are persistent in the environment, they cannot break into less toxic components in nature, and may enter groundwater and drinking water resources.

2.3. Conventional Treatment Methods for CWW

Conventional treatment methods for wastewater use a combination of physical, chemical, and biological treatments, which show varying degrees of performance for removing pollutants such as organic matter, nutrients, solids, and heavy metals [15]. The conventional method for wastewater treatment includes several processes, such as flotation, ion exchange, adsorption, and sediment, that do have the capacity to remove heavy metals from wastewater. This is achieved through the transfer of ions from the solution phase to the solid phase (referred to as sorption) and includes precipitation reactions and adsorption. This transfer can be a physical or chemical process depending on the nature of the elements [56]. Several different treatment methods exist for removing heavy metals, particularly for industrial wastewaters, but these produce copious amounts of heavy metals as a byproduct. The literature shows that each method for treating heavy metals in industrial wastewater does have a different level of efficiency [57]. Municipal wastewater is another source of heavy metal pollution, which is increasing due to rapid urbanization and population growth. Methods for municipal wastewater treatment involving primary settling, sorption technology, and filtration methods have all shown some capacity for removing cadmium, chromium, copper, lead, and zinc ions in municipal wastewater [58].

Carwash wastewater consists of various contaminants that can be partially or completely removed with conventional treatment methods. However, the facility needed to fully remove carwash contaminants from the wastewater stream is complex and expensive. If a region's CWW generated is not regulated, as may be the case in many regions, the generated wastewater is directly discharged from the carwash to the sewage system without any kind of treatment. At minimum, CWW should receive primary treatment such as filtration and coagulation to an acceptable level before discharging to the sewage system or into water bodies [5]. Because CWW treatment should be done right at the source, i.e., within each carwash facility, the wastewater stream can provide an immediate source of recycled greywater if treated to an accepted level.

One study examined how carwash wastewater can be recycled and reused in the same carwash center through a filtration process [14]. An integrated carwash wastewater treatment system was developed in Malaysia. This method was designed at the lab scale and carwash wastewater was sampled in one of the local carwash stations located in Johor, Malaysia. The efficiency of this conventional treatment method was evaluated by measuring DO, pH, COD, and turbidity. This treatment method includes natural coagulant and filtration by sand and gravel, and was effective for removing these measured contaminants and deemed feasible for reuse in the same facility [14]. However, no research or study exists to the authors' knowledge on how CWW can be recycled with acceptable removal of specifically heavy metals.

3. LID Technologies for Heavy Metal Remediation

Low-impact development technologies mitigate the negative effects of urbanization and the growth of impervious surfaces in the environment by helping to control water pollution levels and stormwater runoff quantities [59]. Furthermore, LID practices are considered sustainable, nature-based solutions that are decentralized designs [10]. LID technologies such as rainwater harvesting, green roofs, permeable pavements, and bioretention sites can control flow rate and pollution at the source [60,61]. In general, LIDs can be classified into systems that are vegetated, and those that are not. This is an important difference, as the water quality remediation mechanisms afforded by each are different and each has its own benefits and disadvantages. Examples of unvegetated LIDs are permeable pavements, rain barrels, and stormwater collection systems that store and hold back water in unvegetated reservoirs [62]. Vegetated LIDs use vegetation in some component of the LID and include bioretention cells (aka rain gardens), grassy swales, and green roofs.

3.1. Vegetated LIDs

Vegetated systems such as bioretention systems can employ physical, chemical, and biological processes for treating contaminants in runoff. The runoff is directed to the LID, where it is allowed to pool and infiltrate and percolate through the vegetated system that includes vegetation at the surface, followed by a mulch layer (may not be present depending on the LID) above the growing media and a drainage system at the bottom if the LID is lined (preventing exfiltration through to surrounding soil). Vegetated LID systems enhance water quality through microbial interactions and uptake by vegetation (biological), sedimentation and filtration (physical), and adsorption and precipitation (chemical) [63]. Table 4 and Figure 1 illustrate the processes affecting water quantity and quality in each component of the vegetated LID system. In Figure 1, the contaminated water stream is shown as an arrow that is initially dark with contamination, directed downward through the system. Processes pulling water losses out of the system are shown as proportionally sized arrows directed out to the left (to represent removal from the system). Processes pulling contaminants out of the system are shown with arrows moving into each component towards the right.

Table 4. The role of each component in a vegetated LID system.

Component	Water Quality Mitigation Role
Ponded layer	Retention of incoming water, pooling of water leading to infiltration [26]
Mulch layer	Prevents clogging, moisture management with some water holding capacity [64]
Vegetation, root zone	Infiltration, contaminant and nutrient uptake [65]
Growing media	Sorption, denitrification, nitrification [66]; adsorption, moisture management [67]; metals removal through chemical processes
Drainage zone	Collects and conveys treated water to the outlet pipe, and prevents washout of soil media [68]

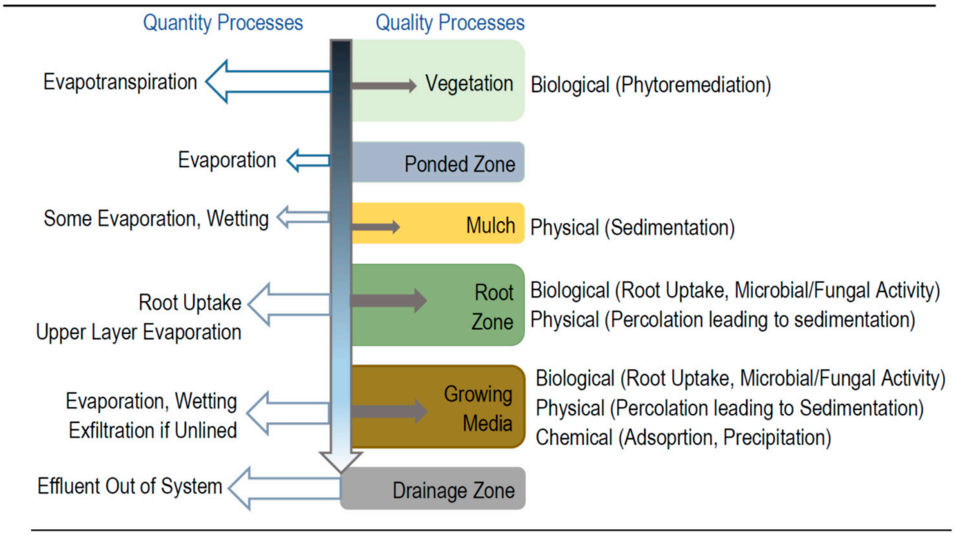

Figure 1. Schematic of vegetated LID metal remediation processes.

One of the most important roles of a vegetated LID is to retain and hold the water stream so that the processes that remove the contaminants are given the length of time needed to be effective [69]. The mulch layer, together with the vegetation roots, provides high infiltration rates needed to allow the pooled water to infiltrate and percolate into and through the subsurface. These layers, together with the growing media, help to capture TSS through the physical mechanism of sedimentation. As Tables 2 and 3 show, CWW can contain very high levels of TSS, particularly for vehicles used in agricultural settings and certain industries.

Plants in a bioretention system are selected by considering the soil condition and climate [70]. Generally native grass, bushes, and trees are recommended, as they are best able to adapt to the soil and weather conditions of each region. Although the role of the vegetation component is to remove contaminants and protect the soil from water erosion, vegetated LID efficacy is highly related to the plant species installed [71,72]. Plants have to be selected based on their efficiency in treatment and adopting to environmental conditions and climate [65]. The literature shows that the vegetation component of an LID can greatly enhance nutrient (total phosphorus and total nitrogen) removal [71] through sedimentation, sorption, filtration, and enhanced denitrification [72]. Some plants showed a better performance in nutrient and heavy metal removal, such as bamboo (*Bambusoideae*), rosea variegata (*Graptophyllum pictum*), the ti plant (*Cordyline fruticosa*), and the umbrella palm plant (*Cyperus alternifolius*) [64]. Furthermore, some studies have shown that using two different plant species will increase the performance of a system's nutrient removal and increase the plants' resistance to adverse environmental conditions [73].

Although microbial activity in the soil and root zone as well as uptake by vegetation can provide for removal of some heavy metals, heavy metal remediation primarily occurs within the soil through chemical processes. The soil found in the growing media of the vegetated LID carries electrical charges that can attract dissolved heavy metals. These processes, together with the physical process of filtration and the chemical processes present, help to reduce these contaminants [65]. Heavy metal removal by vegetated LID systems have been proven efficient in some cases, with observations of copper, zinc, and lead ion removal reported up to 81%, 79%, and 75%, respectively, over a period of three months [74]. A study in China demonstrated that a vegetated LID was able to remove cadmium, copper, iron, manganese, nickel, lead, and zinc ions [75].

The literature shows that vegetated LIDs are a beneficial, cost-effective, and eco-friendly treatment practice to remove contaminants from stormwater runoff, which also contains similar contaminants to carwash wastewater, such as heavy metals and TSS, but in lower concentrations. Vegetated LIDs not only mitigate polluted stormwater runoff, but can also can help to reduce urban heat island effects and air pollution [76], as well as many other beneficial qualities for the community. The primary drawbacks to vegetated LIDs are the high level of seasonal and annual maintenance, the time required to achieve maturity and treatment levels, the uncertainty in the biological activity in the LID at any time, and the inherently low storage capacity. Given the volumes of water generated at carwash facilities, the size of the vegetated LID would need to be large in order to treat the levels of water that are typically experienced. Because stormwater tends to be intermittent and certainly of smaller volumes than CWW, vegetated LIDs are often small in physical size, and thus, easily installed at the source.

3.2. Unvegetated LIDs

A schematic of a non-vegetated LID system is shown in Figure 2. Like Figure 1, it shows the relevant removal mechanisms afforded by this system and the general water flow pathway. Although non-vegetated LIDs technically include rain barrels and certain reservoirs, generally, this category of LID is dominated by permeable pavements systems, which are certainly more complex in design than a rain barrel, for example. Hence, Figure 2 is modelled after a general permeable pavement. Permeable pavement systems generally involve a highly permeable cover layer that absorbs the runoff with an extremely high infiltration rate [32]. These covers may be comprised of porous concrete, porous asphalt, pavers, or other highly permeable material that can support significant traffic loads. Below this cover is a sand course separated by a thin geotextile membrane, below which is the reservoir course filled with large diameter aggregate. The system absorbs and retains a large percentage of the wastewater stream with few losses. This mitigates the quantities that can lead to flooding [77], and allows the needed retention time for quality mitigation processes.

As Figure 2 shows, the contrast between vegetated and unvegetated LID systems is that the latter can only provide physical remediation processes. There is some chemical remediation and only minor biological processes, if any. These systems allow sedimentation and filtration of metals [72], which are normally dissolved. In addition, Figure 2 also shows that the amount of water retention this kind of system can provide is very large and markedly higher than that provided by vegetated systems of similar size. Heavy metal removal by permeable pavements depends on multiple factors such as weather conditions and climate factors, contaminant load, system design, and infiltration rates achieved [64]. Both types of LID act like filters. In the unvegetated LID, the pores in the surface layer collect particles, as do the pores in the sand layer. The geotextile is highly effective in removing contaminants [78], but is not a component that can easily be cleaned like the surface of a pavement (with power washing, for example). The stream of wastewater that reaches the aggregate layer does undergo some further remediation [31], as it is a reservoir with great storage capacity that provides settling and sedimentation. It is the movement and storage within the LIDs systems that allow this system to remove large quantities of TSS and some TDS.

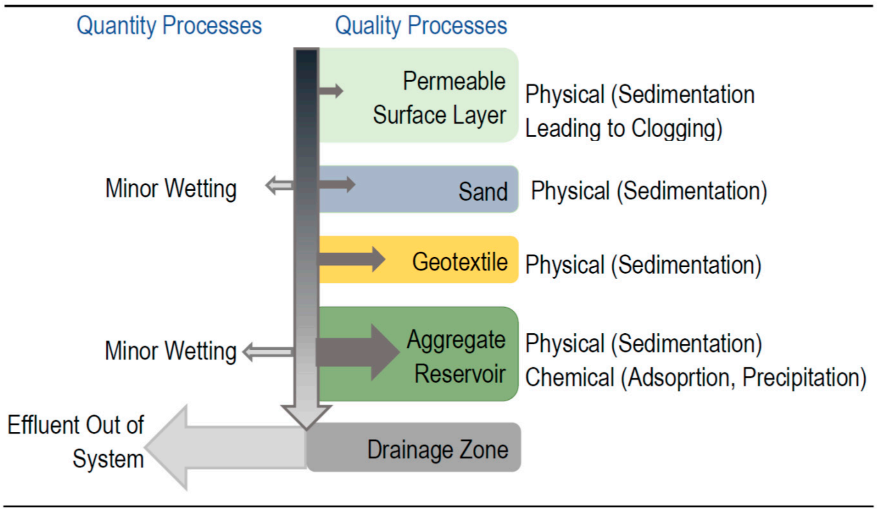

Figure 2. Schematic of unvegetated LID metal remediation processes.

4. Discussion of LID Potential for Use in CWW Treatment

Pavement provides volume and retention and physical mechanisms as well as chemical processes when reacting with aggregate. In addition, plants and trees in bioretention sites can uptake heavy metals and nutrients from the polluted water along with the soil. Carwash wastewater contains a wide range of contaminants such as detergents, heavy metals, sand, oil, and grease. Trees and shrubs have shown an effective performance in heavy metal uptake and in removing nitrate and phosphate through bioretention systems [79]. In recent years, a handful of developed countries having been using eco-friendly methods for removing contaminants and heavy metals from stormwater runoff [80]. This suggests that LID may be a potential method for in-situ CWW treatment that can remove pollution from wastewater and prepare recycled water for the same use at the same center. Treatment trains are systems of LIDs that combine different types of LIDs to get a more complete removal process for the variety of contaminants in the wastewater stream [17,79]. Thus, LID treatment trains that involve an unvegetated permeable pavement system that provides storage and removes large quantities of solids in the early stages of the flow, combined with a vegetated system to provide further enhancement and biological remediation, can be a sustainable solution to CWW treatment in a wide variety of climates, geographies, and economies.

To the Authors' knowledge, the literature contains very few LID-type systems that are used to mitigate CWW. In Malaysia [41], TSS and TP were measured in carwash wastewater (CWW) before and after treatment in three vegetated LIDs (rain garden mesocosms). This study was done to evaluate the performance of these rain gardens for reducing carwash water pollution, especially surfactants. TSS reduction was 84–95%, and surfactant reduction was reported to range from 89–96%. This study showed that bioretention efficient water pollution reduction in CWW [41].

In India, a low-impact development (LID) was developed to treat CWW from a carwash facility located in a large agricultural area specifically intended for cleaning vehicles used in farming. Carwash wastewater was monitored pre- and post-treatment to evaluate the efficiency of this method, which relied on both filtration through permeable pavers combined with vegetation supported by Silva Cells®. Electrical conductivity, pH, and turbidity were monitored, but the research is ongoing [8]. In a joint co-operative with researchers in India, researchers in Canada are conducting a study for treating carwash wastewater by using a stable filtration technology and phytoremediation. In this treatment method, the carwash wastewater flows through a highly permeable surface where some contaminants are removed by primary filtration, and the rest of the impurities are absorbed by the trees planted in this research site [81]. The primary distinctions in the Canadian site include the fact that it is facility dedicated to research only, and the permeable pavement system and the vegetated component (trees only) are integrated into one unit. Poplar (*Populus deltoides*) and alder (*Alnus rubra*) trees are planted within Silva Cells® with a growing media that are then enclosed by an aggregate reservoir. The objectives of this particular study are to determine the ability of these trees to absorb copious amounts of CWW contaminated with heavy metals while maintaining the benefits of vegetated systems. Tree health is monitored through chlorophyll content and leaf area index (LAI). Relationships between the treatment efficacy and tree characteristics are determined to provide design parameters and a better understanding of the role of phytoremediation to clean the types of contaminants found in CWW facilities supporting rural and agricultural transport systems.

5. Conclusions

This paper reviewed the literature pertaining to carwash wastewater characteristics and assessed the potential for low-impact development technologies to remediate heavy metal contamination in carwash wastewater, with the intention of making the practice more sustainable and potentially providing a water resource. The amount of water consumption in carwash stations varies around the world and depends on the region, type of operation (manual or automated), and size and operation of the vehicles. The scant literature shows that amounts vary between 35 and 400 L/car, which can translate into millions of liters of freshwater generated every year that require treatment. CWW contains a wide range of contaminants, including heavy metals; sand and dust; detergents; surfactants; phosphates; grease; waxes; hydrofluoric acid; petroleum hydrocarbon wastes such as motor oil, diesel, and petroleum; as well as unacceptable levels of acidity and turbidity. Given the hazardous nature of many of these contaminants, some (but not all) jurisdictions require that CWW be treated before being discharged to receiving waters, and Malaysia stands out as a leader in addressing CWW management.

LID technologies are sustainable, green infrastructure solutions implemented at the source and using little to no energy. These nature-based systems show an acceptable performance in removing contaminants such as heavy metals from stormwater and may have potential for CWW treatment. However, they remain a largely unexplored alternative to conventional methods of CWW treatment. The Authors propose that a treatment train-style system that combines the storage, retention, and physical water quality remediation afforded by permeable pavement systems, with a vegetated LID that enhances contaminant removal through chemical and biological processes, may provide a viable system for producing acceptable levels of water quality in the effluent that can potentially be reused. Future work on evaluating the potential for LIDs for treating CWW should also consider computing ecological and carbon footprints for the region of interest in the application.

Author Contributions: Conceptualization, M.T., C.V., R.G. and C.P.C.; data curation, M.T.; formal analysis, M.T. and C.V.; funding acquisition, R.G. and C.V.; investigation, M.T.; methodology, M.T. and C.V.; project administration, C.V.; resources, C.V.; supervision, C.V.; validation, C.V. and M.T.; visualization, M.T. and C.V.; writing—original draft, M.T. and C.V.; writing—review and editing, M.T., C.V., R.G. and C.P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by funds from CFI-JELF 32294, NSERC RGPIN-2015-05096, and a University of Victoria Internal Research Grant (2017).

Data Availability Statement: Data sharing not applicable No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors are grateful to the five reviewers who took the time to review this work and provide such valuable feedback. Their insights greatly elevated the quality of this work.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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