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Filter media for storm water treatment in sustainable cities: A review

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Storm water treatment and management will be more important in the future due to climate changes, e.g., more frequent, and intense rain events that might cause flooding. To meet these challenges, low impact development (LID) technologies such as paved surfaces, green roofs and various bioretention systems have been suggested in urban areas. Various filter media, natural and engineered materials, have been used to amend the LID solutions in field experiments enhancing the removal of different contaminants present in storm water of different kinds. Researchers suggest locally available low-cost media having high capacity to remove pollutants. Other parameters to take into consideration when selecting filter media are clogging, hydraulic parameters. Climatic conditions in different regions, e.g., temperate, or cold climatic zones, do not seem to have a large impact on performance on LID solutions.

KEYWORDS

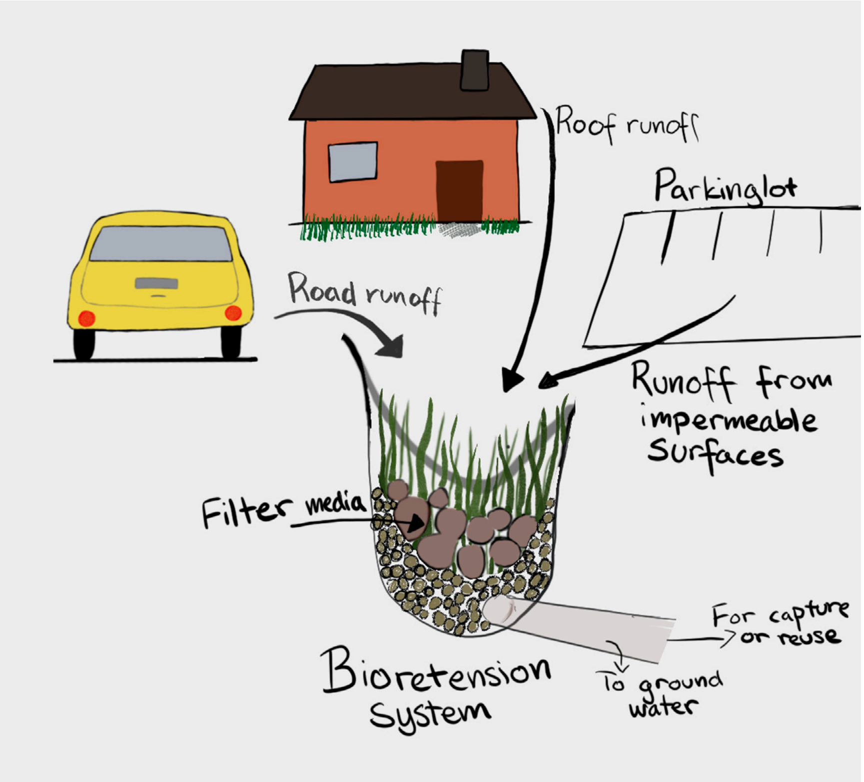
low impact development technology, field trial, nutrients, heavy metals, lowcost material

1 Introduction

The world is facing new challenges due to climate changes such as higher temperatures, more frequent and intense precipitation occasions, and rising sea levels (Doblas-Reyes et al., 2021). These changes are necessary to take into consideration when planning for new urban districts or, when adapting existing ones to new climatic conditions (Madsen et al., 2019). An issue that needs to be taken into consideration is for instance the management of storm water. Volumes of storm water, or urban runoff, generated during heavy rains that falls within a short period are expected to increase and it is necessary to manage these volumes of waters to prevent floodings such as those we have seen in different cities all over the world in recent years, see for instance Madsen et al. (2019) and Yang, D. et al. (2019) on the floodings in Copenhagen, Denmark, and in Houston, United States, respectively.

World over, measures are taken in urban areas to handle large volumes of water that arise in connection to heavy rainfalls. In China, large districts or cities have been transformed into “sponges” or “sponge cities” in which water can be managed through green solutions (Kongjian, 2018; Xianga et al., 2019). Small-scale solutions to improve the capacity to handle water in already existing areas have also attracted interest in recent years. In Stockholm, Sweden, an already existing park area in the central part of the city, has been adapted to meet the more frequent and intense rains by ditches and biofilters planted with vegetation (Stockholms Stad, 2023).

However, the composition of storm water is complex and varies due to land use (Goonetillekea et al., 2005) and season (Hallberg et al., 2007). The characteristics of storm water quality is also expected to change due to the climate changes. Based on computer simulation experiments, Borris et al. (2014) showed that the concentrations of TSS



GRAPHICAL ABSTRACT
Conceptual model of storm water flowing from roads, roofs, and impermeable surfaces to a bioretention systems in which filter media is incorporated for treatment and management of the storm water before it is being released into the environment.

probably would change as a response to new expected patterns in rain intensities and durations. Furthermore, Borris et al. (2016) could show expected changes in concentrations of heavy metals as well, and in addition, relate these to different climate scenarios.

Scientists suggest various methods to manage urban storm water. Low Impact Development (LID) are suggested by several (Mohanty et al., 2018; Deng, 2020; Shahrokh Hamedani et al., 2021). Shafique and Kim (2017) claim these solutions to be smart and innovative storm water systems to reduce negative effects of increased urbanization and climate change. The aims with LID treatment technologies are several; one aim is to increase the infiltration possibilities in urban areas otherwise covered with impermeable layers or paved with asphalt. An increased infiltration could also lead to higher retention of storm water runoff. Another aim is to treat the storm water commonly polluted with nutrients, heavy metals, and organic substances (Mohanty et al., 2018). Some LID technology solution can offer higher infiltration, retention, and treatment of storm water runoff at the same time. Figure 1 shows a conceptual model of storm water treatment in a LID treatment facility. LID technology solutions consist of different bioretention facilities such as green roofs, grassed swales, infiltration beds, rain gardens and constructed wetlands (Mohanty et al., 2018; Deng, 2020). Other environmentally engineered systems are permeable pavement systems. Not all these facilities could be implemented within urban areas due to large land area needed, constructed wetlands demand large land areas for instance and cannot always be integrated into planned or already existing areas. Facilities that promote infiltration as well as treatment of storm water, e.g., infiltration beds, rain gardens and green roofs, can be partially planted with vegetation that contribute to the infiltration through their root systems, but they also favor treatment of storm water Yang, F. et al. (2019). LID technology solutions can be implemented in different kinds of climate zones; temperate and cold climate regions, they also perform in cold climate regions (Roseen et al., 2009).

To further improve infiltration, retention and treatment of storm water, low-cost filter media, could be incorporated in new or retro-fitted into existing treatment facilities (Mohanty et al., 2018; Yang et al., 2019; Deng, 2020; Xie et al., 2021). Filter media intended for removal of various pollutants from storm water have been investigated, mostly in laboratory investigations, e.g., in batch and column studies. In these, a wide range of natural and engineered filter media have been studied regarding their capacities to remove various pollutants such as nutrients and heavy metals (Färm, 2002; Wu and Zhou, 2009; Chang et al., 2010; Norris et al., 2013; Reddy et al., 2014; Lim et al., 2015; Huber et al., 2016a; Genç-Fuhrman et al., 2016; Hilbig et al., 2017; Sounthararajah et al., 2017). More recently, Okaikue-Woodi et al. (2020) presented a review on filter materials for storm water management. Their study is focused on a vast range of filter media, natural as well as engineered, available in the United States, and the physical and chemical properties favorable for removal of pollutants present in storm water. Most of the results presented by Okaikue-Woodi et al. (2020) are based on laboratory

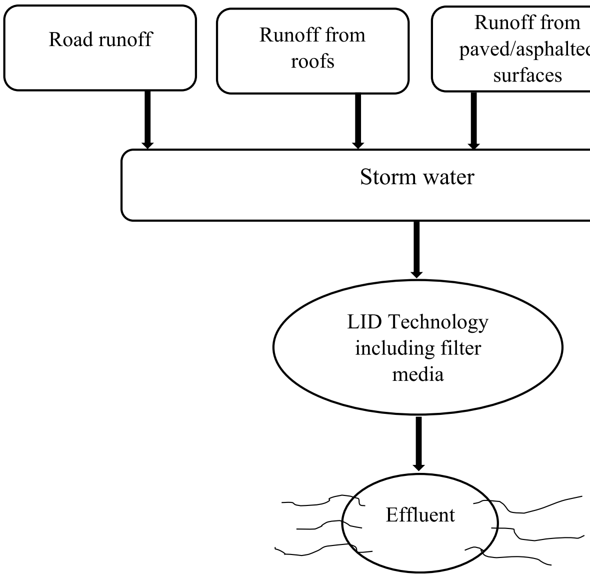


FIGURE 1
Conceptual model of storm water treatment and management in Low Impact Development technologies including filter media.

experiments in which synthetic storm water has been investigated in batch or column investigations.

Even though many filter media have been investigated in laboratory studies and suggested for further testing in field conditions, far from all have been tested in real-life conditions. It was concluded by Okaikue-Woodi et al. (2020) that more research is needed to learn more about the practical use of filter media in real-life situations, a conclusion also presented by Kaya et al. (2022). The aim of this paper is therefore to review and discuss some LID technology based storm water treatment facilities that comprise a filter media under field conditions where real-life storm water, or synthetic storm water, is treated regarding a variety of pollutants, and discuss how these can add to the management of storm water.

2 Materials and methods

The present article is based on a literature review. Articles about storm water treatment in LID based technologies comprising filter media have been collected to give an overview of treatment technologies used, filter media investigated, and results obtained in the field.

Two scientific databases have been used for the literature search: Web of Science and Scopus, two multidisciplinary databases covering topics relevant for the review. The keywords (or variants) that have been used are filter media; filter material, storm water/stormwater, urban runoff, and low impact development technology/LID. Only articles describing field studies have been included.

3 Results

Researchers have investigated different filter media and their capacities to remove pollutants from storm water under real conditions. In Figure 1, a conceptual model of different types of storm water entering a LID solution is shown. In this section, LID technology-based solutions including filter media for storm water management in field applications are described. A variety of filter media have been investigated, see Table 1. In the following presentation, the reviewed filter media have been listed in alphabetical order.

3.1 Basalt

In Sydney, Australia, Sounthararajah et al. (2017) performed a pilot-scale investigation of a permeable pavement system (PPS). Basalt was used as filter media along with zeolite. The intention of the study was to investigate the removal of heavy metals from a synthetic storm water containing cadmium (Cd), Copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn). The pilot test was run for 80 h corresponding to runoff in 10 years of rain fall in Sydney. At the end of the experiment, Sounthararajah et al. (2017) could observe that the cumulative removal for the metals by the basalt varied between 38% and 67%. The authors concluded that the metal concentrations in the effluent from the basalt filter did not meet the recommended values stated by Australian and New Zealand guidelines. In previous laboratory experiments, basalt had been evaluated as a medium with high removal capacity regarding heavy metals which was the reason for Sounthararajah et al. (2017) to test it in the pilot-scale investigation.

3.2 Biochar

Biochar is a solid residue consisting of carbon and ashes that remains after a thermochemical conversion of organic matter at high temperature in an environment free of oxygen, e.g., pyrolysis.

TABLE 1 Filter media reported in the literature.

Filter media	Natural/ Engineered	Information about filter media used	Location	Referencess
Basalt	Natural	Commercially available	Sydney, Australia	Sounthararajah et al. (2017)
Biochar	Engineered	Biochar feedstock 60% Monterey Pine, 20% Eucalyptus, 10% Bay Laurel, and 10% mixed hardwood and softwood. Pyrolysis temperature peaked at 394°C	Stanford, California, United States	Kranner et al. (2019)
	Engineered	Commercially available high-temperature gasification biochar	Sonoma, California, United States	Teixidó et al. (2022)
Light-weight aggregates (LWA)	Engineered	Filter media consisting of 66% LWA, 30% humus and 4% clay	Tartu Estonia	Teemusk and Mander (2007)
	Engineered	Filter media consisting of 66% LWA, 30% humus and 4% clay	Tartu, Estonia	Teemusk and Mander (2007)
	Engineered	Produced by dredged sediments from port	Cleveland, Ohio, United States	Liu and Coffman (2016)
	Engineered	Pumice or expanded clay LWA (90%) and compost (10%)	Hoboken, New Jersey, United States	Cheng et al. (2022)
Sand	Natural	Fine and coarse sands free from soil, organics, and clay. The fine sand: 10% passing through a 150 mm sieve; 90% passing through a 300 mm sieve; the coarse sand 10% passing through a 500 mm sieve; 90% passing through a 1000 mm sieve. d60 = d10 < 3 for both sands	Sydney, Australia	Kandasamy et al. (2009)
	Natural	Commercially available ASTM C33 grade sand mixed with 5% commercially available iron filings	Sonoma, California, United States	Teixidó et al. (2022)
	Natural	Locally available silt loam soil (65% quartz, 10% albite, 10% muscovite, 7.5% anorthite, 5% kaolinite and 2.5% montmorillonite and sand (100% quartz)	Nantes, France	Fardel et al. (2020)
	Natural	Commercially available sand (1.2–3 mm) and coarse sand (3–5 mm). Both sands were washed	Stockholm, Sweden	Hallberg et al. (2007)
Water treatment residuals (WTR)	Engineered	Aluminum-derived WTR used as an amendment to sand	Burlington, Vermont, United States	Ament et al. (2022)
	Engineered	Granulated aluminum derived WTR	Hoboken, New Jersey, United States	Nagara et al. (2022)
	Engineered	Spent lime drinking water treatment residuals used in the form of a dewatered filter cake	Maplewood, Minnesota United States	Kuster et al. (2022)
Woodchips	Natural	No information	Cheonan City, South Korea	Geronimo et al. (2019)
	Natural	No information	Cheonan City, South Korea	Maniquiz-Redillas and Kim (2016)
	Natural	No information	Sonoma, California, United States	Teixidó et al. (2022)
Zeolites	Natural	Locally available at Werris Creek, New South Wales, Australia)	Sydney, Australia	Sounthararajah et al. (2017)
	Engineered (synthetic)	Commercially available, chemical formula $Na_2O*Al_2O_3*2.4SiO_2*nH_2O$, grain size 1–8 mm	Stockholm, Sweden	Milovanović et al. (2022)

Different types of organic matter can be used as feedstock in the pyrolysis process along with differences in the pyrolysis process (temperature and duration of the process), which means that the biochar has different properties (Xie et al., 2021). Biochar has been investigated regarding its removal capacities for various pollutants in laboratory experiments with promising results (Mohanty et al., 2014; Afrooz and Boehm, 2017; Sang et al., 2019; Biswal et al., 2022; Kaya et al., 2022). Some researchers have also performed pilot-scale experiments in the laboratory. Biochar has also been tested in some field experiments, see Table 2. The table shows that different kinds of LID technologies have been studied and that the experiment periods have varied. Kranner et al. (2019) investigated biochar in laboratory column studies but were uncertain whether the results would be generalizable to field conditions. In a following, simulated field experiment, sand and, sand mixed with biochar, were tested by Kranner et al. (2019). Filters consisting of sand and sand enriched

TABLE 2 Low Impact Development facilities including biochar as filter media.

Type of LID technology	Period of experiment	Targeted pollutants	Results in brief	Referencess
Sand filter enriched with biochar (comparison to sand filters)	14 months	*Escherichia coli*	During the first half of the experiment, sand filters enriched with biochar performed better than sand filters. During the rest of the experiment, no differences were observed	Kranner et al. (2019)
Storm water treatment train (Step I: sand + iron for removal of PO_4^{3}-P, Step II: Bioreactor with woodchip plus aeration, Step III: Sand filled columns enriched with iron, biochar and/or manganese oxides)	8 months	PO_4-P, NO_3-N, trace metals and persistent, mobile, and toxic trace organic contaminants	First step removed PO_4-P to roughly 16%. Step 2 removed NO_3-N to 98% and step 3, removed trace metals and other pollutants to roughly 80%. Sand filled columns enriched with biochar removed polar trace organic contaminants with a retention order of 2,4-D $<$ atrazine $<$ TCEP $<$ fipronil $<$ 1H-benzotriazole $<$ diuron. Order of metal removal followed was Pb $>$ Cd $>$ Cu/Ni $>$ Zn	Teixidó et al. (2022)

with biochar were dosed with natural storm water for approximately 14 months to investigate the removal of *Escherichia coli.* During the first 7 months of the experiment, the sand filters enriched with biochar performed better than the sand filters. During the following months until the end of the experiment, no differences could be observed between the filters. Kranner et al. (2019) did also study the impact of the presence of saturated zones in the filters but could observe that these were not significant.

An onsite experiments using biochar has been performed in which Teixidó et al. (2022) investigated a pilot-scale "storm water treatment train". The treatment train consisted of different steps targeting different pollutants. The first step consisted of a sand filter enhanced with iron to remove phosphate. The second step targeted nitrate by using a woodchip bioreactor coupled to an aeration step. Following was a set of columns filled with sand amended with iron and in addition enriched with biochar and/or manganese oxides for the removal of trace metals and other toxic contaminants. The "train" was fed with real-life storm water runoff for 8 months. After the investigation period, Teixidó et al. (2022) could observe that the removal of nitrate in the bioreactor was nearly 100% while it was less for phosphate removal in the sand filled columns in which phosphate broke through the iron-rich sand. During the first 4 months of the experiment, Teixidó et al. (2022) observed 80% removal of metals and organic compounds in the columns filled with sand mixed with biochar and manganese oxides respectively. The authors concluded that, under the conditions at the study site, the removal of nutrients would be sustained for about a decade, but the organic compounds would not.

3.3 Lightweight aggregates

Lightweight aggregates have been investigated in numerous laboratory investigations (Vohla et al., 2011) and the material has also been used in full-scale in the field for treatment of domestic wastewater (Jenssen et al., 2010). Lightweight aggregates has also been investigated as filter material in green roofs, see Table 3. Investigated LWA material have been produced by different raw materials and various pollutants have been targeted. In Tartu, Estonia, Teemusk and Mander, (2007) carried out a study with the aim to investigate the functioning of a green roof in which LWA was used as filter media. The authors compared the lightweight green roof, partly vegetated by various plants, with roofs with modified bituminous membrane roofs under local weather conditions regarding storm water retention potential and quality of the runoff. The experiment was run between June 2004 and April

TABLE 3 Low Impact Development facilities including lightweight aggregates (LWA) as filter media.

Type of LID technology	Period of experiment	Targeted pollutants	Results in brief	Referencess
Green roof	11 months	Tot-N, Tot-P, COD and BOD_7	Higher concentrations of pollutants when slow runoff compared to rapid runoff at storm events	Teemusk & Mander (2007)
Green roofs (comparison with sod roofs)	6 years	pH, BOD7, COD, Tot-P, PO_4-P, Tot-N, NH_4-N and NO_3-N, SO_4 and Ca-Mg salt	Higher values of pH, BOD_7, Tot-P and PO_4-P in runoff from LWA roofs than from sod roofs. Conc. of COD, Tot-N, SO_4 and Ca-Mg salt were higher in the sod roofs than in green roofs. NPK-fertilized green roofs had higher conc. of N and P than non-fertilized LWA roofs	Teemusk et al. (2011)
Green roof (dredged-produced LWA compared to conventional produced LWA)	6 weeks	-	Higher water retention if green roofs with dredged derived LWA compared to conventional LWA	Liu & Coffman (2016)
Green roof	5 years	Tot-P	Initially high release of Tot-P during the experimental period, but gradually decreasing	Cheng et al. (2022)

TABLE 4 Low Impact Development facilities including sand as filter media.

Type of LID technology	Period of experiment	Targeted pollutants	Results in brief	Referencess
Sand filtration devise	18 months	*E.coli*, SS, N, P and Zn	Removal of pollutants to the same extent in both fine and coarse sands	Kandasamy et al., 2009
Two types of bio-retention systems, a surface sand filter, a subsurface gravel wetland, a street tree, and porous asphalt	2 years	TSS, total petroleum hydrocarbons-diesel range TPH-D, DIN (comprised of NO_3-N, NO_2-N, NH_4-N) tot-P and tot-Zn.	Investigated LID facilities showed a high performance during winter months. Frozen filter media did not reduce the performance.	Roseen et al. (2009)
Swales	3 months	Zn, PAHs (pyrene and phenanthrene) and glyphosphate	Reductions of pollutants was 67%–90% for Zn and ≥89% for the other pollutants	Fardel et al. (2020)
Experimental pilot-scale filter system	7 months	Cu and Zn	Removal of Tot-Cu was 67% and 93% for Tot-Zn. Removal of dissolved Zn was 87% and 19% for dissolved Zn	Hallberg et al. (2007)

2005. During the experiment, three rain events and one snow melting period were analyzed allowing for sampling during three different water runoff conditions. The targeted pollutants in the experiment were total-N, total-P, COD and BOD_7. The results showed that the green roof with LWA was able to retain precipitation in the form of light rain to about 90% provided that the precipitation events did not occur too close to each other in time. Teemusk and Mander (2007) could also report that the green roof did not retain precipitation in the form of heavy rain. During the snow melting period, the snow on top of the filter media melted in 1 day while the filter media melted in just under 2 weeks. Further, Teemusk and Mander (2007) report that the quality of the runoff from the green roof were both positive and negative. They observed higher concentrations of targeted pollutants in the runoff when the runoff was slow compared to when heavy rainfalls occurred washing the pollutants out of the roof. In the melting runoff from the snow, concentrations of the pollutants were higher since atmospheric pollutants had accumulated in the snow. These findings lead to the conclusion that the green roof worked as a storage; pollutants were accumulated in the filter media and washed out during intensive precipitation occasions. In summary, Teemusk and Mander (2007) believe that green roofs have more advantages than disadvantages, but that continued research is of interest.

In another study, run from August 2004 to April 2009 in Teemusk and Mander, (2007) investigated roof runoff from ten green and sod roofs, the filter media in the former consisted of LWA products. The monitoring covered 21 rain or snow melt occasions and included pH, BOD_7, COD, total-P, PO_4-P, total-N, NH_4-N, NO_3-N, SO_4 and Ca/Mg-salt. The authors observed that the green roofs had a significant impact on the water quality. In general, they found that the runoff from the green roofs had higher values of pH, BOD_7, total-P and PO_4-P compared to the runoff from the sod roofs. On the other hand, COD, total-N, SO_4, and Ca- and Mg-salts were higher in the sod roofs. Green roofs that had been fertilized with NPK-fertilizer showed higher concentrations of nutrients compared to green roofs which had not been fertilized. Concentrations of NH_4-N and NO_3-N in roof runoff were similar from both types of roofs. During the entire experimental period, Teemusk et al. (2011) could observe that the concentrations of the targeted compounds in the roof runoff slowly decreased with exception for the concentrations of Ca- and Mg salts that remained stable. Teemusk et al. (2011) suggested this was caused by the LWA material. It was concluded that quality of the roof runoff from green roofs were lower compared to the precipitation especially regarding nutrient content, but Teemusk et al. (2011) suggested that the nutrient rich runoff could be used for fertilization in the countryside. Lightweight aggregates were also used in a study by Liu and Coffman (2016). Initially, they describe the production of lightweight aggregates from dredged sediments recovered from ports and harbors along Ohio's Lake Erie coast, United States. Further, said material was thoroughly investigated in the laboratory regarding different properties. Finally, the dredged LWA material was tested regarding its potential as growing media in a microcosms green roof installation in the field in Cleveland, United States of America. The aim with the experiment was to compare the dredged lightweight aggregates to conventional LWA products used for green roofs regarding the moisture of the materials. Liu and Coffman (2016) exposed the LWA materials to moisture for 6 weeks, water was supplied either by irrigation or via precipitation. At the end of the experiment, their results showed that the water retention capacity of LWAs depends on the conditions of the production of the aggregates, in general the water retention ranged between 11% and 23%, thus increasing the water retention in the lightweight aggregates compared to conventional systems for green roofs. Liu and Coffman (2016) concluded that the dredged lightweight aggregates would be a suitable filter media in green roof constructions, especially since it was produced by a material otherwise deposited at landfill sites. They concluded that the production process, if slightly changed, could be designed as to remove various targeted pollutants such as phosphorus and nitrogen. Further, Liu and Coffman (2016) mention another benefit with green roofs as storm water management constructions; they contribute to cooling in cities during periods of high temperature.

An experiment consisting of 32 pilot-scale experimental green roofs were conducted by Cheng et al. (2022) in New Jersey, United States of America. The experiment was run from 2017 until 2022 covering four growing seasons including 38 storm events. The aim with the experiment was to measure phosphorus contribution from the roofs planted with sedum species to the roof runoff. The green roof media was a LWA material (90%) based on either pumice or expanded clay, the rest (10%) consisted of compost. During the experimental period, the runoff from the green roofs, and a control roof, were sampled regarding precipitation, volumes of runoff and total-P measured as event mean concentrations in the discharge from

TABLE 5 Low Impact Development facilities including water treatment residuals (WTR) as filter media.

Type of LID technology	Period of experiment	Targeted pollutants	Results in brief	Referencess
Field bioretention system	2 years	P species (soluble reactive P, dissolved organic P, particulate P, and tot- P)	All P species reduced in WTR filter media	Ament et al. (2022)
Catch basin	6 months	P, Cu, Pb, and Zn	Reduction of dissolved P, Cu, and Zn, as well as Tot-P, Cu, Pb, and Zn	Nagara et al. (2022)
Full-scale P removal structure	5 years	P constituents, heavy metals, total suspended solids (TSS), and pH. Toxicity (assessed using *Ceriodaphnia dubia*)	Reduction of Tot- P (70.9%), dissolved reactive P (78.5%), dissolved P (74.7%), TSS (58.5%). Significant reduction in heavy metals	Kuster et al. (2022)

the roofs. Cheng et al. (2022) could observe that the concentration of total-P from the green roofs was elevated compared to concentrations from the control roof; Cheng et al. (2022) could also observe that the concentrations of total-P decreased over the monitoring period, and it was suggested that this was due to retention of P in the green roofs. Down-stream the green roofs; Cheng et al. (2022) tested permeable reactive barriers or as additives in the base substrate used for the green roofs. Zeolites, wood-derived biochar, and oat hull-derived biochar were used. The addition of zeolites (20%) in the base material on the roofs, showed lower concentrations of total-P compared to roof without amendment. Cheng et al. (2022) concluded therefore that the excessive content of P in the base material exceeded the needs of the sedum species resulting in release of P from the green roofs.

3.4 Sand

Sand is a filter medium that is naturally occurring world over and thus, it has been the subject of many investigations in both laboratory and field experiments regarding the removal of a variety of pollutants. Field studies using sand as filter media for removal of pollutants from storm water have been conducted by several scientists, a few examples are presented in Table 4. As can be seen from the table, the LID technologies investigated are of various kinds, the experimental periods differ as do the targeted pollutants in the studies. Kandasamy et al. (2008) investigated a sand filtration device in sub-urban Sydney, Australia. The authors had two aims with the investigation; the first with the aim to determine whether sand filters were efficient regarding removal of pollutants. The second aim was to compare the removal efficiency of a fine and a coarse sand. Storm water reaching the sand filter device originated from a catchment containing commercial and residential areas, roads, but also parkland and recreational areas. Removal of fecal coliforms, suspended solids, nutrients and Zn as representative pollutants in storm water were investigated. At the termination of the study, Kandasamy et al. (2008) could observe that both the fine and the coarse sand removed targeted pollutants to the same extent which was similar to results previously reported in the literature. Kandasamy et al. (2008) also observed that the sand filters were coated with a crust of fine organic material decreasing the infiltration of storm water over time.

A field experiment described by Fardel et al. (2020) comprises two swales receiving storm water roof runoff in Nantes, France. One of the swales, the standard swale, was constructed from a natural soil (silt loam) while the other consisted of silt loam embankments surrounding a central part of sand that served as filter. Both swales were fed with roof runoff from a galvanized roof. The aim with the study was to investigate the treatment efficiencies of four micropollutants, e.g., zinc (Zn), PAHs (pyrene and phenanthrene) and glyphosphate. The experiment was run between March 24 and June 28 in 2018 and, consisted of 12 simulated runs. The 6 first runs included runoff from a roof, and the last 6 runs included the roof runoff spiked with synthetic micropollutants. The authors firstly compared the removal of pollutants in the two swales, and secondly, the concentration reduction between the overflow and infiltrated water. Finally, they investigated how the pathway of the inflowing water influenced the removal of the targeted pollutants. At the end of the investigation period, Fardel et al. (2020) observed that the standard swale reduced the targeted micropollutants in the infiltrated water with 35%–85% while the corresponding values for the overflow water was observed to range between 65% and 100%. Reductions of pollutants in the filtering swale was reported to be 67%–90% for Zn and ≥89% for the other micropollutants. The corresponding values for the standard swale were lower for all pollutants. Based on the observations, Fardel et al. (2020) concluded that filtering swales were preferable to standard swales.

Hallberg et al. (2007) describe a pilot study in Stockholm, Sweden, in which storm water from a road was filtered through sand-filled columns after having passed a grit chamber. The sand used was a standard sand. The road runoff originates from a major thoroughfare in Stockholm. The major aim with the study was to investigate the removal of particle-bound copper (Cu) and zinc (Zn). The experiment was run for 7 months and covered 24 road runoff events, both rain and snowmelt. From the study, it was observed that Cu and Zn present in the road runoff were removed by the sand if loading ranged between 16.8 and 20 L/m^2·h. The removal of total Cu was reported to be 67% and the corresponding removal of total Zn was 93%. Dissolved Zn was removed to 87% while the corresponding removal for dissolved Cu was 19%. At the end of the experiment, the sand showed potential to remove the investigated metals, but Hallberg et al. (2007) suspect that the metal concentrations might exceed permitted values in the longer run.

3.5 Water treatment residuals

Water treatment residuals (WTR), a by-product generated in drinking water production when Al- or Fe-based coagulants are

TABLE 6 Low Impact Development facilities including woodchip as filter media.

Type of LID technology	Period of experiment	Targeted pollutants	Results in brief	Referencess
Infiltration trench (woodchips, sand, and gravel)	7 years	TSS, Tot-N, Tot-P (including organic P, apatite P), non-apatite inorganic P and labile P)	Higher conc. of N and P were found in silt compared to sand and gravel. Conc. of N varied more than conc. of P explained by efficient P-removal mechanisms. Pre-treatment of stormwater in LID facilities enhanced removal of N and P through sedimentation. No results reported on impact of woodchips	Geronimo et al. (2019)
Hybrid wetland (woodchips, sand, and gravel)				
Two infiltration trenches (woodchips, sand, gravel, and white pebbles)	4 years	TSS, particulate and dissolved Zn, Pb, Cu, Ni, Cr, Cd, and Fe	Conc. of heavy metals increased proportionally with the conc. of TSS. Fe was particulate-bound, thus easiest to remove followed by Zn and Pb. Cd, Cr, Cu and Ni were dissolved and difficult to remove During larger storm events, all LID systems performed well regarding particulate-bound metals compared to smaller storm events in which more dissolved metals were observed	Maniquiz-Redillas and Kim (2016)
Tree box filter (woodchip, woodchip mulch, sand, gravel, and white pebbles)				
Rain garden (woodchip, woodchip mulch, sand, and gravel)				
Two hybrid-constructed wetlands				
Storm water treatment train (Step II: Woodchip bioreactor plus aeration)	8 months	NO_3-N	Consistent removal of NO_3-N during experimental period, reduction 98%. Removal rate in bioreactor was 9 ± 3.3 g N·m^{-3}· d^{-1}	Teixidó et al. (2022)

added to remove particulate and dissolved constituents. The material has attracted attention as filter media in recent years, especially regarding removal of P and heavy metals (Deng, 2020; Nagara et al., 2022). Xu et al. (2018) has, based on a literature review, identified WTR as a media with high potential for removal of pollutants in storm water. A few field investigations based on WTR included in different LID facilities have been performed in recent years, see Table 5. From the table, it can be seen that the types of LID technologies have varied as well as experimental periods and targeted pollutants.

In a field experiment, WTR were tested in a bioretention experiment described by Ament et al. (2022). The aim with the investigation was to study the removal of various P species, e.g., soluble reactive P, dissolved organic P, particulate P, and total-P present in storm water from a road. The experiment was run for 2 years. In the experiment, the WTR media was compared to a control consisting of washed gravel, pea stones, sand, and compost. When the experiment was terminated, Ament et al. (2022) could observe that all P species were reduced in both filter media, but higher for all P species in the WTR media, probably due to P saturation of the control. Ament et al. (2022) also investigated the water flow through the bioretention media and whether they would leach heavy metals. Ament et al. (2022) reported that there were nothing affecting the hydraulic performance of the WTR media, nor of the control. Ament et al. (2022) concluded that WTR effectively could reduce and retain P species without interference from hydraulic performances (Table 6).

Nagara et al. (2022) also investigated aluminum based WTR in a field trial with the aim to investigate the removal P and heavy metals (Cu, Pb and Zn) in storm water originating from a parking lot in New Jersey, United States of America. The WTR material was added to a catch basin as WTR granules. The experiment lasted approximately 6 months covering 12 storm events that were monitored. Nagara et al. (2022) could observe that the granulated WTR reduced dissolved P, Cu and Zn but also total- P, total-Cu, total-Pb and total-Zn. Except for the promising results regarding removal of targeted pollutants, Nagara et al. (2022) also highlights the fact that the WTR is a by-product that otherwise would have been disposed at a landfill site at a high cost and therefore is an interesting filter media.

In Minnesota, United States, Kuster et al. (2022) investigated spent lime drinking water treatment residual (DWTR), in a full-scale facility intended for removal of phosphorus from storm water, however, other pollutants were measured as well. The treatment facility was run for 5 years. The DWTR was dewatered at the local water treatment plant and used in the treatment facility without any further processing. Storm water generated in a commercial area with impervious surfaces, was passed through the DWTR before entering a nearby lake. Kuster et al. (2022) could observe that the DWTR reduced all P species investigated. Significant reductions in TSS and heavy metals were also reported by Kuster et al. (2022). Based on their findings during the long-term observations, they concluded that DWTR is a suitable material for removal of phosphorus.

3.6 Woodchips

Woodchips, small pieces of wood from cutting or chipping trees or wood waste, have attracted attention as filter media in LID technologies for removal of various pollutants in storm water, see Table 6. Some researchers have investigated woodchips in different kinds of LID technologies in which the removal of a range of pollutants have been in focus. Geronimo et al. (2019) investigated three different LID technologies, e.g., an infiltration trench, a small hybrid wetland and hybrid sub-surface flow wetland in Cheonan City, South Korea, from May 2009 to October 2016. The intention was to study the effect of pre-treatment of storm water runoff regarding removal of nutrients by investigating the

TABLE 7 Low Impact Development facilities including zeolites as filter media.

Type of LID technology	Period of experiment	Targeted pollutants	Results in brief	Referencess
Pilot-scale permeable pavement system	80 h (corresponding to 10 years runoff)	Cd, Cu, Ni, Pb and Zn	Cumulative removal of metals varied between 41% and 72%	Sounthararajah et al. (2017)
Treatment system including an underground filter unit through which stormwater was pumped upwards	16 months	Cu, Zn, but also Na and Al	Reduction of total and dissolved Cu; 52%–82% and 48%–85%. Corre-sponding values for total and dissolved Zn were 50%–94% and 48%–94%. Conc. of Tot-Na was 4 times higher in effluent than in influent. Same pattern for Al	Milovanović et al. (2022)

distribution of nutrients in the different LID technologies containing filter media, e.g., woodchip, sand, and gravel in the infiltration trench and the small hybrid wetland; bio-ceramic, sand, and gravel in the hybrid sub-surface flow wetland. Storm water from roads and parking lots was used in the study. The authors monitored selected storm events during the experiment, under which hydrological well as hydraulic conditions varied. The composition of the storm flows also fluctuated. At the termination of the experiment, Geronimo et al. (2019) could observe that silt or sand, captured in the pre-treatment ranged from 9% to 92%. Higher concentrations of N and P were found in silt particles compared to sand particles. The authors concluded that pre-treatment of storm water reinforced removal of nutrients, a finding of interest in the design of LID technologies. Geronimo et al. (2019) did not mention the potential role of filter media used i.

A parallel investigation was performed by Maniquiz-Redillas and Kim (2016), also in Cheonan City, South Korea. Their intention was to investigate the efficiency of six LID technology systems (e.g., two infiltration trenches containing woodchips, sand, gravel and white pebbles; one tree box filter containing woodchip, woodchip mulch, sand, gravel and white pebbles; one rain garden containing woodchip, woodchip mulch, sand, and gravel; two hybrid-constructed wetlands containing sand and gravel) to remove particulate and dissolved heavy metals (Cd, Cr, Cu, Fe, Ni, Pb and Zn) from storm water originating from roads, parking lots and roofs. The trial lasted for 4 years (2010-2014) and during that time, eighty-two precipitation events were monitored., most af them with light rain. Maniquiz-Redillas and Kim (2016) reported that the concentrations of metals followed the concentration of TSS. Among the metals, Fe was the easiest to remove followed by Zn and Pb. The other metals were not as easily removed, the author suggested these were dissolved rather than particulate bound. Maniquiz-Redillas and Kim (2016) also reported that all systems performed well regarding removal of particulate bound metals, especially during heavier storm events. Neither Maniquiz-Redillas and Kim (2016) discussed the potential role of the different filter media used for the removal of pollutants.

3.7 Zeolites

Zeolites are porous minerals composed of alumina-silicates; they occur naturally but they can also be produced industrially. A common area of use is that they are used as adsorption materials. Several studies have been performed using zeolites as filter material in laboratory experiments. In batch tests, Reddy et al. (2014) investigated zeolites as filter material for the removal of N and P using simulated storm water with promising results. Wu and Zhou (2009) investigated zeolites mixed with a porous iron sorbent using synthetic storm water in batch tests and reported. In column tests, Färm (2002) investigated the removal of heavy metals by zeolites with varying results.

Zeolites have also been tested in field applications, see Table 7. In these investigations, zeolites have been used in different kinds of LID systems and mainly removal of heavy metals have been of interest. In a pilot-scale investigation of a permeable pavement system, in Sydney, Australia, Sounthararajah et al. (2017) used natural Australian zeolites along with basalt as filter media. The authors used synthetic storm water with the intention to investigate the removal of five heavy metals: cadmium (Cd), Copper (Cu), nickel (Ni), lead (Pb) and zinc (Zn). The pilot-test was run for 80 h corresponding to runoff in 10 years of rain fall in Sydney. At the end of the experiment, it could be observed that the cumulative removal for the metals by the zeolite varied between 41% and 72%. The authors could conclude that the metal concentrations in the effluent did not meet the recommended values stated by Australian and New Zealand guidelines. When adding a post-treatment filter consisting of a sodium titanate nano-fibrous (TNF) material and granular activated carbon (GAC), the removal of targeted metals increased, and the effluent easily met the required standards.

In another field experiment, Milovanović et al. (2022) investigated zeolites as filter material in a facility treating storm water from an area in Stockholm comprising a copper roof and a park. The target pollutants were copper (Cu) and zinc (Zn), but sodium (Na) and aluminum (Al) were also evaluated. The study was run for 16 months and included seven sampling occasions. Milovanović et al. (2022) report a high reduction of total and dissolved Cu; 52%–82% and 48%–85% respectively. Although the reduction of copper was high in the filter medium, the outgoing concentrations exceeded the emission limits recommended by the authorities. What also could be observed was a decline in the efficiency of the filter media over time and the authors concluded that this was due to saturation of the filter material.

4 Discussion

Many scientists agree that we face climate changes that will have an impact on the frequency and intensity of precipitation occasions. In urbanized areas, the volumes of storm waters and their compositions, will be factors necessary to take into consideration. The storm water must go somewhere and, in many cases also be purified. The type and design of treatment facilities depends on local conditions such as land area available and volumes and composition of storm water. In already existing areas, LID solutions could be implemented at several spots in a city. It has been proved that paved or asphalted areas can be replaced by LID solutions. In the city of Copenhagen, Denmark, this transformation started after the intense and heavy precipitation occasions in 2011 and 2012. The planning of measurements is described in a special plan for the city addressing the future management of storm water related to new climate conditions (Københavns Kommunes, 2012).

Several researchers advocate LID solutions including filter media for improved management and treatment of storm water (Chang et al., 2010; Mohanty et al., 2018; Yang et al., 2019; Deng, 2020; Xie et al., 2021). The following discussion will focus on LID solutions with incorporated filter media and characteristics of importance for said media.

4.1 Low impact development solutions based on filter media

Low Impact Development solutions with filter media have proven useful for storm water treatment in urban areas (Xu et al., 2018). These solutions can, as described in the literature, be included in urban areas. To include storm water treatment facilities in green areas such as common parks is one way. Treatment facilities based on filter materials could in this case be areas where the polluted storm water could infiltrate and pass through a filter media layer with a high capacity to remove pollutants (Milovanović et al., 2022) and at the same time, also retain, the storm water runoff. Bioretention beds, such as swales are areas where water can infiltrate and where removal of pollutants could take place at the same (Fardel et al., 2020). Rain beds in which sand mixed with biochar have been implemented in Stockholm, and the biochar is expected to contribute to the removal of pollutants as well as to increase the infiltration, thus preventing flooding.

Paved surfaces is another type of solution that might be designed to improve the treatment of storm water by including a filter media that removes pollutants. Sounthararajah et al. (2017) have described a permeable paved surface in which basalt and zeolites were tested regarding removal of heavy metals.

Another way to improve the storm water treatment is to use green roofs in which filter materials could be incorporated. Teemusk and Mander (2007) showed that filter media in green roofs could contribute to the retention of water and in addition, also to the reduction of some heavy metals. The disadvantages using a filter media in a green roof would occur when the filter media is saturated with metals (or other pollutants targeted). Then, the filter media must be replaced in order to preserve the capacity to remove the pollutant(s). Liu and Coffman (2016) also investigated lightweight aggregates (LWA) as a potential media to incorporate into the growing media of green roofs to increase the water retention capacity. Their results showed that the water retention capacity of LWAs depends on the conditions of the production of the aggregates, in general the water retention ranged between 11% and 23%, thus increasing the water retention compared to conventional systems for green roofs. The advantages of using filter media in green roof constructions is that the filter both retains water and removes metals. Disadvantages would arise the day when the filter media is saturated or clogged, then it needs to be replaced to preserve the removal and retention capacities. The problems of clogging by filter media are described by Le Coustumer et al. (2012) who stress that clogging is one design parameter that needs to be taken into consideration. Kandra et al. (2014) investigated the smoothness and shape of a variety of filter media and concluded that these properties had low impact on clogging and sedimentation. On the other hand, flow-through rate effected clogging and rate of sedimentation. Another aspect to take into consideration is the weight of the medium, Teemusk and Mander (2007) and Liu and Coffman (2016) could observe that the lightweight aggregates increased the water retention in the green roofs, thus increasing the weight of the roof.

Except from the reported capacity of pollutants removal in LID solutions, other advantages are that they are regarded as low-cost and easy to implement. The storm water treatment facilities described in the literature, are spread all over the world. They range from full-scale applications to pilot-scale applications and, they have been performed under various local conditions. Some applications mimic conventional bioretention systems like the swales investigated by Fardel et al. (2020) or green roofs as described by Teemusk and Mander (2007) and Liu and Coffman (2016). Other treatment facilities are specially designed such as the storm water treatment train described by Teixidó et al. (2022).

In most field trials reported in the literature, the reduction or removal of a few selected pollutants by filter media have been investigated. Even though the treatment facility has performed well regarding the targeted pollutants, it can be expected that all pollutants present in the storm water will not be removed due to the design of the facility and/or the selection of filter media. A combination of treatment steps using different filter media in each step as described by Teixidó et al. (2022) could be a solution. Storm water containing a wide range of pollutants could be treated and depending on the storm water composition, it would be possible to design the treatment facility for specific pollutants.

Concerns for use of LID technologies in cold climate has been raised (Roseen et al., 2009). LID technologies have, however, proved to perform in different parts of the world (Table 1), and under various climatic conditions. Roseen et al. (2009 studied seasonal variations in removal of pollutants, penetration of frost in filter media, and hydraulic performance by LID solutions in six LID solutions (two bioretention systems, a surface sand filter, a subsurface gravel wetland, a street tree and a system based on porous asphalt) in New Hampshire, US, between 2004 and 2006. The aim was to compare the LID solutions to conventional Best Management Practices (BMPs) and manufactured storm water treatment systems. The authors could observe that LID solutions showed small differences in performance over the different seasons compared to the other types of storm water treatment systems that performed better in summer. They could also observe a decline in performance during cold periods in the smaller systems depending on particle settling time. Roseen et al. (2009) concluded that the LID solutions have a high functionality in cold climate even though the filter media is frozen and that these findings were beneficial for the use of LID systems also in cold climate regions. Roseen et al. (2009) did not discuss the filter media and their role for the performance in the LID solutions investigated. The article by Roseen et al. (2009) is the only article in this review, that describe the performance of filter media in cold climate regions, thus it is difficult to conclude that this would be the case in all cold climate regions. Even though the findings b reported by Roseen et al. (2009) indicates that at least some filter media can be used in cold climate regions, further research should be carried out to confirm the findings by Roseen et al. (2009).

The functionality of filter media in LID solutions in other parts of the world with different climatic conditions has also been proved in the literature reviewed. Maniquiz-Redillas and Kim (2016) describe different LID solutions in Cheonan, South Korea. In addition to removal of pollutants, they investigated a range of hydrologic and hydraulic parameters such as event rainfall depth, duration of rainfall and runoff, intensity of rainfall, volumes of runoff, flow rate, antecedent dry day (ADD) and hydraulic retention time. Maniquiz-Redillas and Kim (2016) observed that reduction of particulate-bound metals was higher during large storm events (>15 mm) compared to smaller storm events (<5 mm). The former however had higher concentrations of dissolved metals. The efficiency of the LID systems regarding removal of particulate-bound metals did not meet the removal demands during high-intensity storm or when concentrations of metals were low. Maniquiz-Redillas and Kim, (2016) therefore identified this as an important design parameter since a LID system needs to be efficient regarding both particulate-bound and dissolved metals. The findings by Maniquiz-Redillas and Kim, (2016) can surely be implemented at other locations with similar climatic conditions in case the composition of the storm water to be treated contain heavy metals. In other climate region with different hydrologic pattern, the design of LID systems might look different. Few of the investigations in this review give descriptions of the climate regarding hydrologic patterns for specific areas or regions, and this might be viewed as a flaw. Hydrologic parameters are of importance for the design of the LID systems, some of them described in the review are pilot-scale trials with controlled "storm events" (Sounthararajah et al. (2017), but in those experiments, factors such as dilution of storm water by precipitation is not included.

Although LID based treatment solutions seem to work, there are reasons why they are not used more widely. In some places, it is not legal to build a LID technology facility considering the authorities' concern that the environment will be damaged. The fears are negative impacts of the experimental design on flooding and effluent water quality according to Afrooz and Boehm (2017). In other cases, authorities responsible for storm water treatment might lack or have an incorrect view of the inspection and maintenance of LID based solutions (Houle et al., 2013). There are however recent surveys of bioretention facilities regarding the operational status, see for instance Beryani et al. (2021).

4.2 Filter media

Chang et al. (2010) state that pollutants can be reduced or removed from storm water using a filter or sorption media. Shahrokh Hamedani et al., 2021 agrees and, claim that "LID treatment performance is highly dependent on the media characteristics.

A wide range of filter media have been investigated regarding removal of pollutants from storm water, e.g., natural materials such as basalt and sand (Kandasamy et al., 2008; Sounthararajah et al., 2017; Fardel et al., 2020; Hallberg et al., 2007), fabricated materials like zeolites and lightweight aggregates (Teemusk and Mander, 2007; Liu and Coffman, 2016) and waste products such as water treatment residuals (Ament et al., 2022; Nagara et al., 2022). Irrespective of origin, they all possess certain properties making them more or less suitable for removal of pollutants.

4.2.1 Characteristics of filter media

Given that filter media incorporated in LID technology is beneficial for the removal of pollutants and for infiltration of storm water into the ground, selection of filter media must be performed. What kind of filter media that is to be selected depends on chemical and physical characteristics promoting removal of targeted pollutants, availability, and cost. Chemical and physical characteristics of filter media have been extensively investigated in laboratory studies before being tested in the field. The choice of filter media for the full or pilot trials described in this review, has, in most cases, been preceded by laboratory experiments in which selected filter materials have shown high capacity to remove one or several specific contaminants in batch or column experiments. The sorption capacity has been suggested as a major property of a filter media used in LID solutions (Deng, 2020). Factors of importance regarding sorption mechanisms could include chemical composition of filter media, its particle size, or its porosity.

A minimum of chemical data on the filter media used in the field investigations reported, have been presented in the literature reviewed, most probably due to previous laboratory investigations. Some information, being chemical composition or physical properties like particle sizes are however reported in Table 1. As can be seen from the table, there are differences between media used within each category. This is importance to keep in mind since materials of the same kind are not uniform. Kaya et al. (2022) mention for instance that biochar are synthesized from various feedstocks under different conditions making the characteristics of the biochar variable, for instance regarding capacities to remove contaminants. Irrespective of filter media, Deng, 2020 points out sorption mechanisms as important for "binding strength, adsorption kinetics, and treatment capacity". Another characteristic for some filter media used, is undesired leaching. Deng (2020) also state that unwanted leaching from the filter media that might have negative impact on water quality in the receiving water body and therefore, is something that must be considered when selecting filter media.

A physical phenomenon that might occur in LID facilities is clogging of the filter media, especially if the system is based on gravity (Hallberg et al., 2007). Clogging is regarded as a major limiting factor for storm water treatment systems (Kandra et al., 2014). In a laboratory study by Kandra et al. (2014), a column experiment was performed with the aim to investigate some physical characteristics of zeolite, scoria, river sand and polymeric glass beads, and the rates of flow-through on the clogging of storm water filters. Semi-synthetic storm water was used in the experiment. Kandra et al. (2014) could observe that neither shape nor smoothness had very little effect on clogging and rate of sediment removal. On the other hand, Kandra et al. (2009) could observe that the flow-through rate had a major impact on both clogging and rate of sediment removal and further field investigations were suggested. To avoid potential problems with clogging in described field studies, different prevention measures have been taken. Kandasamy et al. (2008) installed a gross pollutant trap preventing pollutants and gravel to enter the sand filter device that otherwise would clog. Geronimo et al. (2019) advocated pre-treatment basins for settling of sediments before the storm water entered the LID facility.

4.2.2 Availability and cost of filter media

Kaya et al. (2022) stress that filter media should be locally available. Natural material might be found onsite or nearby the LID technology solution. Sand or other natural soils are examples of material present everywhere, and in several of the field trials, sand or any other soil present at the site have been used in the treatment facility (Hallberg et al., 2007; Fardel et al., 2020). Along with sand, silt and/or loam, has been investigated (Fardel et al., 2020). If the sand or soil has suitable properties promoting removal of pollutants and allowing storm water infiltration, sand would be a good solution, the filter media is in place and costly transports having negative impacts on the environment can be avoided. Other scientists using locally available filter media are Sounthararajah et al. (2017) who used naturally occurring zeolites and basalt. Apart from being practical to be able to use a material that is already in place, it also helps to reduce costs for transportation.

In case there are no suitable natural material available, engineered filter media based on locally available raw materials (minerals and bedrock) could be a sound choice if processing is simple and low-cost. LWA products are normally based on clay materials but can also be produced using dredged sediments as described by Liu and Coffman (2016). The use of locally available raw materials for production of filter media is therefore another option. By-products from various industrial activities might be another way to find suitable filter media, either as in "pure" state as for instance the dewatered WTR in form of a cake used by Kuster et al. (2022) or the engineered granulated WTR used by Nagara et al. (2022). Since WTR are generated in drinking water treatment plants that are found in many cities worldwide, this material will be locally available in many places. Therefore, this material would be a suitable filter media unless there are other choices.

Local availability of filter media has benefits, not only regarding the environment, but also the cost. LID technologies are per definition low-cost facilities (Xu et al., 2018) and thus, low-cost materials with high capacity to remove pollutants in the treatment facilities should be preferable (Liu and Coffman, 2016; Deng, 2020). The media might have a low price or even be free of charge. The filter media tested in the field trials reported in the literature could all be regarded as low-cost for various reasons. Local availability has been mentioned, but it also means that the filter media is produced using raw material at a low cost, or even a raw material for free supposing that the material otherwise would have been discarded at a landfill site. Liu and Coffman (2016) describe the production of a light-weight aggregate product made by dredged material from ports, material that normally was disposed of at landfill sites. They showed that this filter media performed well regarding metal removal, but they also saw benefits regarding production costs and environmental concerns. Water treatment Residues is another filter media produced at a low cost (Nagara et al., 2022). It is a by-product that previously has been regarded as a waste product that could be disposed of at landfill sites at a high cost. Since the discovery that it could be used for filtering of storm water with promising results, it is certainly regarded as a low-cost media (Deng, 2020; Nagara et al., 2022) and since it is widespread worldwide, it should also have the potential to be widely used.

Several of the field experiments described in the literature have not been in operation for any length of time and, therefore it has not always been possible to report when the filter materials have become saturated. The lifetime of a filter material affects the cost, the longer the time until saturation is achieved, the cheaper the material will be. In none of the articles reviewed have the authors discussed the costs for filter media investigated, even though many agree the cost being a crucial factor to take into consideration when selecting filter media. What also should be taken into consideration when selecting filter media is the composition of the storm water. A complex composition in which several different kinds of pollutants are present, e.g., nutrients, heavy metals, and organic compounds, might demand for several filter media, each with a high capacity to remove a specific pollutant as suggested by Ryan et al. (2010). If several filter media are to be used, this could be done as described by Teixidó et al. (2022) who used a "storm water treatment train" consisting of several steps in which each a specific pollutant was targeted. How this treatment train could be designed depends on pollutants present in the storm water. Another way to use several filter media would be a mixture of two or several filter media. Biochar has for instance been mixed with sand to improve the removal of pollutants (Kranner et al., 2019). Teixidó et al. (2022) mixed sand, iron and biochar to achieve a high removal capacity.

5 Conclusion

The aim with this article was to review, and discuss few real-life examples of storm water treatment facilities, in some cases based on LID solutions, which comprise filter media. Based on the literature the following conclusions can be made.

- The LID treatment facilities in the reported studies have *per se* performed adequately. They are however difficult to compare since not only the facilities differ in design, choice of filter media and storm water used; the local conditions, e.g., climate, and length of operation in which the studies have been performed also differs widely. LID treatment facilities have performed well in

temperate regions but also during both summer and winter in cold climate regions.
- Selection of filter media should be based on its capacity to remove pollutants, local availability and low-cost. Other parameters that need to be taken into consideration are storm water composition, hydraulic aspects and potential pre-treatment to avoid clogging. Climatic conditions might also be considered.
- Further studies on the filter media used in LID technology-based systems are needed.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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