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Review

A Review of Green Roof Applications for Managing Urban Stormwater in Different Climatic Zones

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Abstract: Many regions have turned to low impact development technologies (LIDs), which are implemented to restore the changes in stormwater runoff that have resulted from urbanization. Green roofs are one typical type of LID. Until now, many studies have validated their roles in managing urban stormwater runoff. However, they have also revealed that the performance of green roofs largely varies with their design configuration, as well as their hydro-climatic exposure. The objectives of this review paper are to statistically synthesize the effects of the influential factors, including design and hydrologic variables, on green roof performance and to explore their effects in different climatic zones. The review's results confirm the differences in the influential variables and, thus, the performance of green roofs in different climatic zones. These are the barriers to knowledge translation among engineering designers, stormwater managers, and policymakers in different climatic zones when implementing green roofs. Consequently, region- or site-specific studies are necessary to implement green roofs with confidence.

Keywords: green roof; climatic zones; design and hydrologic variables; hydrologic performance; water quality performance

1. Introduction

The rapid increase in impervious surfaces due to urbanization across the world not only enhances the pressure on managing stormwater runoff quantity, but also calls for the need for managing stormwater runoff quality to prevent further degradation. Traditionally, centralized stormwater management strategies, for instance, the use of a stormwater drainage/convey system plus end-of-pipe stormwater ponds, have often been applied; however, such strategies have been constrained by the following factors: (1) the large space required for constructing management infrastructure, (2) high construction costs, and (3) the high cost of infrastructure maintenance, rehabilitation, and replacement. As a result, many municipalities and regions across the world have increasingly adopted low impact development technologies (LIDs) as the preferred alternative approach to control and treat stormwater at or in proximity to the source of stormwater runoff. A LID's target is to mimic or maintain the pre-development hydrology of a site by promoting evapotranspiration, infiltration, and/or groundwater recharge.

A green roof (also called a living roof), which is a roof of a building partially or completely covered with a growing medium and vegetation, is one typical type of LID. To date, many studies have been conducted to assess the benefits of green roofs by investigating laboratory-, pilot- and field-scale facilities. The existing body of knowledge proves the effectiveness of green roofs in managing urban stormwater runoff quantity and quality in many regions, while also revealing the need to link their function to climatic exposure due to their regional and/or climate-specific nature. The survival of vegetation would impose challenges on green roof implementation in arid or semi-arid climatic regions, for instance. Both the hydrologic behavior and water quality performance of green roofs are also dependent on meteorological conditions aside from their design. Consequently, the local or regional climatic conditions should be taken into consideration when designing green roofs. It can be argued that caution needs to be paid when translating knowledge among different regions. Therefore, the objectives of this review paper are to synthesize the effects of the design and hydrologic variables on green roof performance and to explore their effects in different climatic zones.

2. Materials and Methods

Peer-reviewed scientific publications, including journal papers and a few conference proceedings and reports, which have investigated the water quantity (hydrologic) and/or water quality performance of pilot- and/or full-scale green roofs, were collected. According to the depth of growing media (also called substrates), green roofs are generally classified into three types, namely extensive green roofs (150 mm or less), semi-intensive green roofs (between 150 mm and 200 mm), and intensive green roofs (200 mm or above). The current prevalent practice is extensive green roofs, as there are no further structural requirements to existing roofs for their implementation. This review paper does not intend to distinguish these three different types of green roofs, as the depth of the growing media was treated as one of the design variables when investigating their effects on green roof performance. The other design variables considered in this paper include the composition of the growing media, roof slope, and type of vegetation. Additionally, the effects of two hydrologic variables, including rainfall characteristics and antecedent dry weather periods (ADWP), which are believed to largely affect green roof behavior, are also investigated.

The hydrologic performance of green roofs has been commonly assessed in terms of stormwater retention rate, which is the percentage of rainfall captured by a green roof in a precipitation event, in the literature [1–3]. In addition to the stormwater retention rate, the peak flow reduction or attenuation rate has also been used for evaluating green roof hydrologic performance. Some studies [3–6] have quantified the peak flow reduction rate relative to the peak flow of a conventional roof, whereas other studies [7–9] have quantified it relative to the peak rate of precipitation. Therefore, the peak flow reduction rate is not included in this review paper. The stormwater retention rate is assessed herein.

When assessing the water quality performance of green roofs, researchers have used different references (such as rainfall water and outflow from a conventional roof) to calculate pollutant removal efficiency. Thus, whether a green roof behaves as a sink or source of pollution would be affected by the selection of the reference. Some researchers [10–12] have compared the outflow quality of a green roof and the quality of rainwater to determine its pollutant removal efficiency, which would be a negative number when a green roof acts as a source of pollution, whereas other researchers have evaluated the water quality performance by comparing the outflow quality of a green roof to that of a comparable conventional roof. Due to these facts, this review paper uses the outflow concentrations of green roofs (rather than the pollutant removal efficiency) to investigate the water quality performance of green roofs. The most common pollutants studied in green roof outflow include several forms of nitrogen and phosphorus and heavy metals [13]. Therefore, the outflow concentrations of several pollutants, including nitrates, ammonia, total nitrogen (TN), phosphate, total phosphorous (TP), cupper (Cu), zinc (Zn), and lead (Pb) have been selected for review.

To compare the means and medians of several samples (such as the stormwater retention rate and outflow water quality concentrations of green roofs among different climatic groups), a one-way analysis of variance (ANOVA) and a Kruskal–Wallis test, which is a non-parametric ANOVA, were conducted at a significance level of 10%. Both the ANOVA and Kruskal–Wallis test are commonly employed statistical analyses. Their test procedures can be found in Sheskin [14]. Arguing the use of these two statistical techniques is beyond the scope of this paper. In addition to the bar graph, a box-whisker plot, which is commonly employed to graphically depict groups of numerical data (samples), was used to aid in the visual presentation of the similarities or differences among the samples.

3. Distribution of Green Roof Studies

The climatic exposure of green roofs was categorized according to the Koppen–Geiger climate classification [15], which is the most widely used system for classifying the world's climates. This approach categorizes climates based on the annual and monthly averages of temperature and precipitation, and it classifies the world into five primary climatic groups: A (tropical), B (dry arid and semi-arid), C (temperate), D (continental), and E (polar). It also further divides each primary climatic group into several sub-climatic groups according to precipitation (the second tier of classification) and air temperature (the third tier of classification). Df represents snow and fully humid, while Dfc denotes snow and fully humid with cool summers in primary Group D, for example. More details on the climate classification system can be found in Kottek et al. [15].

Table 1 provides the explanation of each primary climatic group (A, B, C, D, and E) and each sub-climatic group, in which studies were identified. Note that the sub-climatic groups classified in the Koppen–Geiger climate classification were not included in the table if no papers were found in the sub-climatic groups. This table also reports the numbers of papers used for each primary climatic group and each sub-climatic group for hydrologic performance and water quality performance, respectively. All these papers [1–10,12,16–82], along with the reported stormwater retention rates, water quality concentrations of outflow, and design and hydrological variables are summarized in Table A1 of the Appendix A. As illustrated in Table 1, the research on green roofs has been concentrated in two primary climatic groups, Group C and Group D, while only a few studies were found to be conducted for Group A and Group B. The uneven distribution of green roof studies is not surprising because the implementation of green roofs and other low impact development technologies (LIDs) is prevalent in well-developed urbanized places, many of which are situated in Group C and Group D. Additionally, the cost might constrain green roof research and, in turn, its implementation in developing places. Several developed countries, for example, Germany, the United States of America (USA), and Canada, have promoted LID research and formulated guidelines/regulations for their wide implementation. Most studies in Group C have been conducted in humid subtropical (Cfa) and temperate oceanic (Cfb) sub-climatic groups, while many study sites in Group D were situated in the sub-climatic group warmer-summer humid continental (Dfb) and only a few studies were in the other two sub-climatic groups Dfa and Dwa. No study has been conducted in Group E, while several studies were found for Group A and Group B. Considering the data availability, the comparisons of green roof performances among the four primary groups (A, B, C, and D) and the comparisons of green roof performances between the two sub-climatic groups (Cfa and Cfb) in Group C were conducted in the following sections.

Table 1. Summary of the characteristics of the primary and sub-climatic groups in which studies were identified and numbers of papers regarding hydrologic and water quality performance.

Climate Group	Description	Characteristics	Number of Papers on Hydrologic Performance	Number of Papers on Water Quality Performance
Group A	**Equatorial climates (Tropical)**	**Tmin ≥ +18 °C**	**4**	**4**
Af	Equatorial rainforest, fully humid	Pmin ≥ 60 mm	4	2
Aw	Equatorial savannah with dry winter	Pmin < 60 mm in winter	0	2

Table 1. *Cont.*

Climate Group	Description	Characteristics	Number of Papers on Hydrologic Performance	Number of Papers on Water Quality Performance
Group B	**Arid climates**	**Pann < 10 Pth**	**2**	**2**
BSk	Cold steppe climate (cold semi-arid climate)	Pann > 5 Pth; Tann < +18 °C	2	2
Group C	**Warm temperate climates**	**−3 °C < Tmin < +18 °C**	**29**	**15**
Cfa	Warm temperate climate, fully humid (hot summer)	Psmin = Pwmin; Pwmax ≤ 3 Psmin; Psmin ≥ 40 mm; Psmax ≤ 10 Pwmin; Tmax ≥ +22 °C	13	10
Cfb	Warm temperate climate, fully humid (warm summer)	Psmin = Pwmin; Pwmax ≤ 3Psmin; Psmin ≥ 40 mm; Psmax ≤ 10 Pwmin; Tmax ≤ +22 °C; at least 4 Tmon ≥ +10 °C	15	3
Csb	Warm temperate climate with dry summer (warm summer)	Psmin < Pwmin; Pwmax >3 Psmin; Psmin < 40 mm; Tmax ≤ +22 °C; at least 4 Tmon ≥ +10 °C	1	2
Group D	**Snow climates (Continental)**	**Tmin ≤ −3 °C**	**25**	**14**
Dfa	Snow climate, fully humid (hot summer)	Psmin = Pwmin; Tmax ≥ +22 °C	3	3
Dfb	Snow climate, fully humid (warm summer)	Psmin = Pwmin; Tmax < +22 °C; at least 4 Tmon ≥ +10 °C	19	9
Dwa	Snow climate with dry winter (monsoon-influenced hot-summer)	Pwmin < Psmin Psmax > 10 Pwmin	3	2
Group E	**Polar climates**	**Tmax < +10 °C**	**0**	**0**

Note: Tann = the annual mean near-surface (2 m) temperature; Tmin = monthly mean temperature of the coldest month; Tmax = monthly mean temperature of the warmest month; Tmon = mean monthly temperature; Pann = accumulated annual precipitation; Pmin = precipitation of the driest month; Pth = a dryness threshold in mm, which depends on Tann and on the annual cycle of precipitation; Psmin = lowest monthly precipitation of the summer months; Psmax = highest monthly precipitation of the summer months; Pwmin = lowest monthly precipitation of the winter months; and Pwmax = highest monthly precipitation of the winter months.

4. Hydrologic Performance of Green Roofs in Different Climatic Groups

4.1. Stormwater Retention Rate

The box-whisker plot of the stormwater retention rate of green roofs in the primary climatic groups is illustrated in Figure 1. Note that the sample size (N) is the sum of all the reported individual measurements from the studies situated in each primary climatic group. The sample size is more than the number of papers for the groups, because there is often more than one individual measurement reported in each paper. The means and medians of the stormwater retention rate of Group A (65.86%/73.00%) and Group B (71.28%/78.10%) were relatively higher than those of Group C (60.24%/63.00%) and Group D (56.04%/57.10%). The reported stormwater retention rates of Group A had a relatively large variation, as the calculated standard deviations of the stormwater retention rates of Groups A, B, C, and D were 34.70%, 24.66%, 30.77%, and 32.04%, respectively. The Kruskal–Wallis test detected the significant difference in the medians of the stormwater retention rate among the primary climatic groups, but the significant difference in the means was not found in the ANOVA test. A similar result also was obtained when comparing the retention rates between Cfa and Cfb, whose medians were significantly different. Overall, the medians of the stormwater retention rate of Group A and Group B were statistically significantly higher than those of Group C and Group D, while, within Group C, the median of the stormwater retention rate of Cfa (95.00%) was significantly higher than that of Cfb (60.23%).

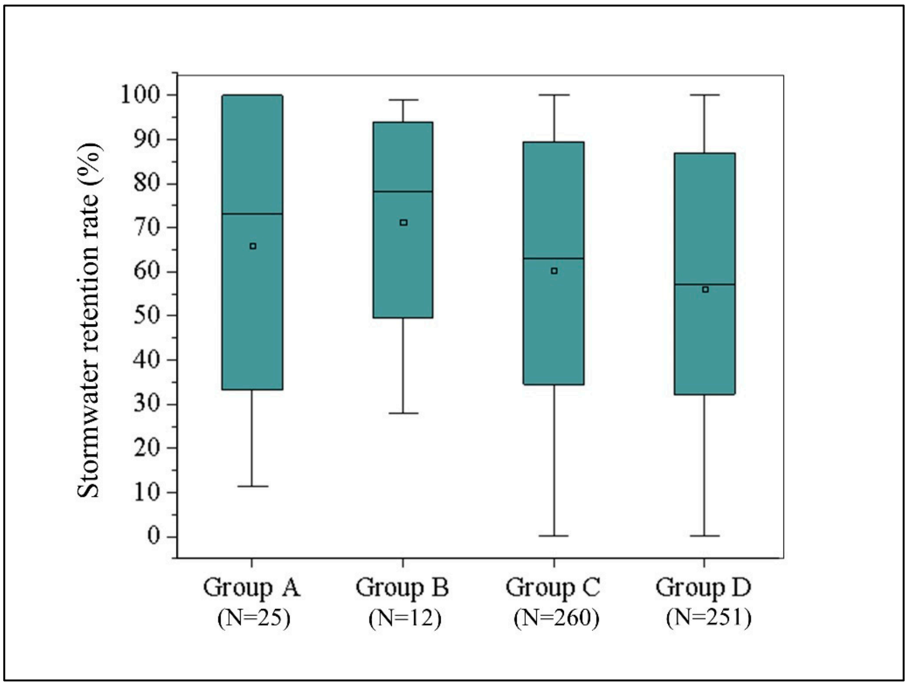

Figure 1. Box-whisker plot of the stormwater retention rates of the four primary climatic groups, respectively. The box covers the range of data between the 25th and 75th percentiles; the whiskers extend to the minimum and maximum values; the median and mean are indicated by the line and the square inside the box, respectively; and N is the sample size.

4.2. Influence of Design Variables on Hydrologic Performance

4.2.1. Growing Media Composition

To avoid a large increase in the structural load of roofs, green roofs are generally constructed using engineered lightweight materials with large particles, such as gravel, pumice, or expanded shale. Thus, green roofs often allow rapid infiltration and, consequently, surface water ponding so that the generation of surface runoff, which can cause the erosion of the growing media in rain events, is avoided [83–85]. It is commonly acknowledged that the growing media largely govern the hydrologic behavior and performance of green roofs, because they primarily determine the water holding/storage capacity and hydraulic conductivity. However, there have been a very limited number of studies [51,71,86] undertaken to link the physical characteristics of the growing media of green roofs to their hydrologic performance. A study by Bengtsson et al. [51] observed that outflow from green roofs (in Group C) did not occur until the media reached field capacity and the outflow eventually equaled the precipitation, which implied the positive association of the lag time of outflow and the field capacity of the growing media, for example. The large range of the stormwater retention rates reported in the literature could be ascribed to the different physical characteristics of the growing media used, which largely varied among and within the primary climatic groups.

The selection of growing media primarily depends on the local availability and cost of materials, as well as the climate [87–89]. The growing media of a green roof usually consists of three main components: lightweight mineral aggregate/recycled materials, sand, and organic matter [85], among which lightweight mineral aggregate material usually in the range of 50–80% by volume is the principal constituent. The selection of aggregate needs to consider many factors, such as performance specification and allowable dead load aside from regional availability and cost [89]. The most common types of aggregate used in North America are expanded slate (typically used in the eastern USA and generally in Group C), expanded clay (commonly used in the mid-western and eastern USA and generally in Group C and Group D), and expanded shale (mostly in western USA and generally in

Group D) [90]. Considering the climatic Group C, heavier aggregates, such as recycled crushed brick, are also used [58,91–94], while volcanic materials (such as pumice and zeolite) are also commonly used in New Zealand and the Pacific Northwest area [84], which are situated in Group C and Group D.

Organic matter, as a secondary constituent of the growing media of green roofs, is especially important for supporting vegetation establishment. Several studies [95,96] have demonstrated the role of organic matter in the enhancement of vegetation establishment and growth. Several types of organic matter, including peat, coir (coconut fiber), compost (such as bark), and biosolid compost have been used. The decomposition of organic matter, which can vary in different climatic groups, should be taken into consideration when determining the organic matter content. The decomposition of organic matter might be slower in green roofs situated in Group B, whereas the seasonal rainfall in Group C could speed the decomposition of excess organic matter and, consequently, result in the loss of media thickness, reductions in saturated hydraulic permeability and air-filled porosity, and migration of fines to separation geotextiles [89]. As illustrated in Table A1, composted bark and peat, which are commercially available, are the most widely used in the climatic groups. The amount of organic matter (either in dry weight or volume) used and/or suggested for use appears to vary among the climatic groups. Regarding the semi-arid climate (Group B), a study by the Alberta Ecoroof Initiative [24] used 5–10% and 50–60% (by dry weight) organic matter; however, the City of Calgary [97] recommended 3–8% (in dry weight) organic matter. Conversely, several studies [37,39,98] conducted concerning Group C used 20%, 7%, and 12.7% of organic matter, respectively, while the American Society for Testing and Materials [89] recommends the addition of 3–15% (by volume) organic matter for this climatic group. The amount of organic matter used/or recommended also varies in a large range for green roofs situated in Group D, for instance, 15–20% in the City of New York [99] and from a very low amount of 2.33% [70] up to 60% in Michigan [100] in the USA.

In addition to organic matter, additives or amendments, such as biochar, silicate-based granules (such as sanoplant), and super-absorbent polymers (such as hydrogel) have been used to increase the water-holding capacity of the growing media [98,101–103]. A study by Nektarios et al. [104] argued that perlite might be suitable for green roofs in the semi-arid climate (Group B) to retain moisture.

4.2.2. Growing Media Depth

Figure 2a shows the box-whisker plot of the growing media depth of the green roofs situated in the primary climatic groups, respectively. The media depth of the green roofs in Group A ranged from 150 to 250 mm (in three green roofs); in Group B, a depth of 150 mm, which is essential for plant survival and growth, was used in two studies, while the media depths in Group C and Group D varied in large ranges from 20 to 350 mm and from 20 to 200 mm, respectively. The average depths of the green roofs in Groups A, B, C, and D were 200, 150, 107, and 94 mm, respectively. The means and medians of the media depths in Group A and Group B were found to be significantly higher than those in Group C and Group D in both the ANOVA and Kruskal–Wallis tests. The higher media depth in Group A and Group B coincided with the detected higher stormwater retention rate in these two climatic groups. Several studies [68,69,105], which were conducted in Group D, argued that the media depth was another factor that played a dominant role in the stormwater retention of green roofs. Additionally, a study conducted in central Pennsylvania for Group D [106] showed that both green roof performance and the survival of plants were promoted by increasing the media depth. Therefore, the relatively high stormwater retention rate observed in Group A and Group B (Figure 1) can be ascribed to the use of relatively thick growing media. There were no significant differences for Group C in the means and medians of the media depths detected between Cfa and Cfb in either of the ANOVA and Kruskal–Wallis tests. Note that the stormwater retention rate was not significantly different in the means, but it was significantly different in the medians between Cfa and Cfb. These results suggest that the effect of the media depth on the stormwater retention is more obvious among the primary climatic groups than among the sub-climatic groups within a primary climatic group.

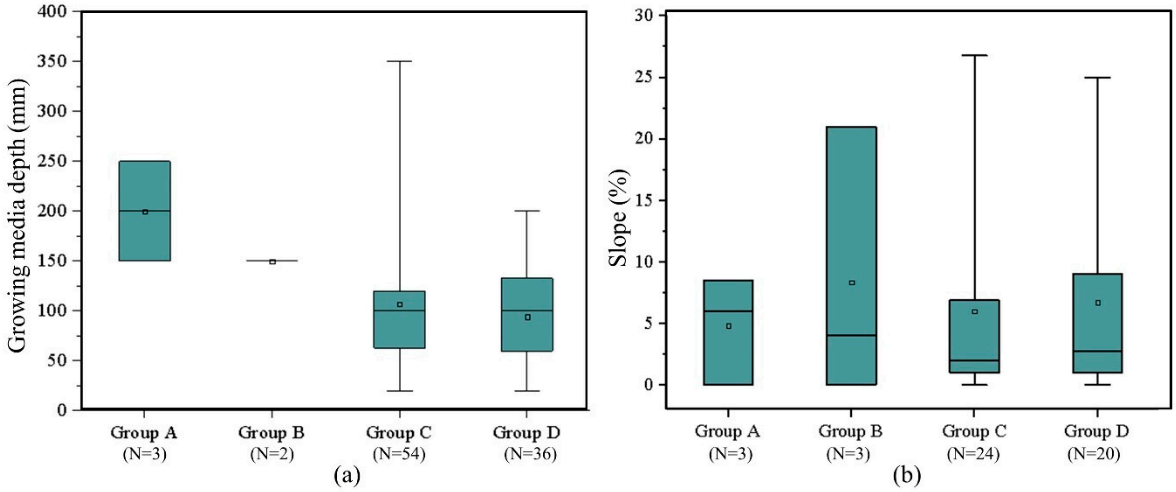

Figure 2. Box-whisker plots of (**a**) growing media depth and (**b**) roof slope of the four primary climatic groups, respectively. The box covers the range of data between the 25th and 75th percentiles; the whiskers extend to the minimum and maximum values; the median and mean are indicated by the line and the square inside the box, respectively; and N is the sample size.

4.2.3. Roof Slope

As displayed by the box-whisker plot of the roof slope in the primary climatic groups in Figure 2b, the variation of the roof slope is in the range from a very small slope (close to zero) to above 25% in Group C and Group D; a large range can also be seen in Group B (maximum up to above 20%), while a relatively small variation range is shown in Group A. Neither the ANOVA nor the Kruskal–Wallis test detected significant differences in the means and medians of the roof slopes in the four primary climatic groups. Similar results also were obtained when comparing the roof slopes in the two sub-climatic groups, Cfa and Cfb.

Regarding individual studies, the observed effects of roof slope on the outflow and the retention capacity of green roofs were not consistent in the climatic groups. Several studies conducted in Group C [13,51] did not identify obvious correlations between the roof slope and the outflow of the green roof, as the vertical percolation process was dominant. However, the negative dependence of the stormwater retention on the roof slope was observed in several other studies, for example [52], in Group C and [68,70] in Group D. The inconsistent results with the absence of significant differences in the roof slope among the climatic groups suggest that the role of the roof slope might not be prominent and can be masked by other dominant factors.

4.2.4. Vegetation

Table A1 shows that several types of vegetation, including sedum, grass, herbaceous plants, and shrubs, have been used for green roofs. Figure 3 further illustrates the percentages of the vegetation types used in each primary climatic group. Native sedums, which are drought tolerant, were adopted in all climatic groups except Group A. Group A often used grasses. Approximately 50% of green roofs were vegetated with sedums in Group B and Group D, while about 50% of green roofs were also planted with grasses in Group B and vegetated with grasses, herbaceous plants, and others in Group D. Approximately 43% of green roofs adopted sedums in Group C; the use of all other types of vegetation also was seen in studies conducted in Group C.

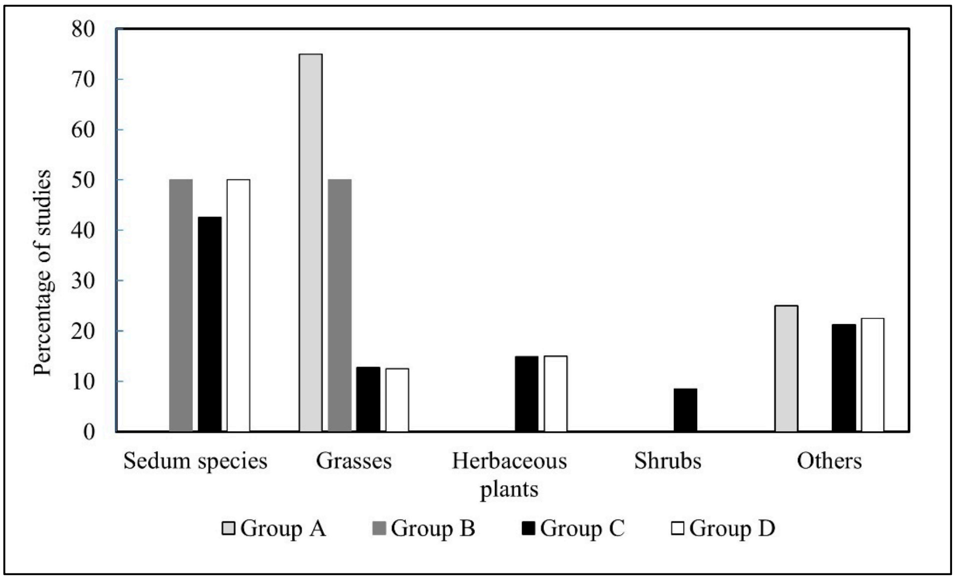

Figure 3. The percentages of green roofs vegetated with sedum species, grasses, herbaceous plants, and shrubs in four primary climatic groups, respectively.

Generally, vegetation can alter the hydrologic behavior of green roofs in several ways as follows: interception, uptake, transpiration, and storage of water [105]. Plant litter can also affect the hydrologic cycle through interception and storage [107]. Figures 1 and 3 illustrate that most green roofs in Group C and Group D were planted with sedum species, and the stormwater retention rate was lower compared with Group A and Group B, in which grasses were often used. These results imply a lesser role of sedums in the stormwater retention of green roofs compared with other types of vegetation. However, as demonstrated by several individual studies in the review, the role of vegetation could be obvious or overwhelmed by other major components of green roofs, such as the growing media. Some studies conducted in Group D [12] and Group C [108] confirmed that vegetation was effective in holding water and slowing water release, while other studies regarding Group D [68,69] concluded that vegetation had less effect on promoting water retention when compared with growing media. All the results demonstrate that vegetation plays a role in green roof hydrologic performance, but its role could be minor due to the dominant roles of other design variables, such as growing media. To better understand the role of vegetation, a more elaborate comparison, such as between green roofs with vegetation and control roofs (without vegetation), might be necessary.

4.3. Influence of Hydrologic Variables on Hydrologic Performance

4.3.1. Antecedent Dry Weather Period (ADWP)

Antecedent soil moisture (ASM) is a crucial influential factor affecting the rainfall–runoff process. The properties of the growing media are the determinant of the maximum possible moisture content in the growing media, while meteorological conditions in the inter-event period would be the other primary driving variable of ASM. A longer antecedent dry weather period (ADWP) allows the growing media to dry out through evapotranspiration and, thus, to have more capacity to accept and retain rainwater in the next rainfall event. Therefore, ADWP would impact the hydrologic behavior of green roofs in rain events indirectly. Regardless of the expected role of ASM or ADWP on the hydrologic performance of green roofs, there are a very limited number of studies focusing on this topic so far.

Among the studies reviewed in this paper, several studies conducted in Group C have investigated the effect of ADWP on the hydrologic performance of green roofs. Razzaghmanesh and Beecham [109] detected an increase in water retention with the increase of ADWP. Another study conducted in the City of Adelaide, Australia [110] observed that the stormwater retention rate of green roofs can reach nearly 100% when the mean ADWP was highest, with a value of 7 days in the summer. These findings are consistent with the observations made by a study conducted in Auckland, New Zealand [44]. However, another study conducted in Sheffield, UK [2], argued that a short ADWP was related to low retention, whereas a long ADWP did not guarantee a high retention rate, because the green roof retention capacity is finite. All these studies suggest the need to characterize ASM or ADWP, which no doubt varies with the climatic conditions, and, thus, to quantify its relationship with the retention capacity of green roofs in different climatic groups.

4.3.2. Rainfall Characteristics

Apart from antecedent dry weather period (ADWP)/or antecedent soil moisture (ASM), the dependence of the hydrologic performance of green roofs on rainfall characteristics has also been investigated in several studies conducted in Group C. A study conducted in Athens, Georgia, USA [41], observed the decline of the stormwater retention rate with the increase in rainfall amount, as retention rates of 88%, 54%, and 48% were reported in small events (<25.4 mm), medium events (25.4–76.2 mm), and large events (>76.2 mm), respectively. However, Simmons et al. [40] observed 100% retention rates in small rain events (<10 mm) and large variations in the stormwater retention rates in 12 mm rain events (26–88%), 28 mm rain events (8–43%), and 49 mm rain events (13–44%). Another study conducted in Germany [110] reported very low retention rates of green roofs in extreme events. Additionally, a study conducted in Malmo, Sweden [51] stated that the degree of the alternation of the outflow hydrograph of green roofs was dependent on rainfall intensity. A study conducted in Lund, Sweden [52] concluded that the lower the rainfall intensity, the larger the retention rate. Although different researchers have used different cutoff values to classify small, medium, and large events, the stormwater retention rate of green roofs is relatively high in small events (in amount and intensity) and low in rain events of high intensity and amount in Group C. This conclusion might also be valid for the other climatic Groups A, B, and D; however, further studies are needed to confirm it.

5. Water Quality Performance of Green Roofs in Different Climatic Groups

5.1. Pollutant Concentrations in Green Roof Outflow

The concentrations of the investigated water quality parameters of green roof outflow are summarized in Table A1. Figure 4 further shows the concentrations in the primary climatic groups, respectively, using box-whisker plots. Both nitrates and phosphates were the common nutrients analyzed in all four primary climatic groups, while the concentrations of other water quality parameters were unavailable for Group A and/or Group B. Obvious differences in the water quality concentrations and their variations among these climatic groups are displayed in Figure 4. The highest means and standard deviations were calculated in Group C for all water quality parameters except phosphate, Cu, and Pb, which had the highest means and/or the largest variations in Group A. Similar results were seen in the medians of the water quality parameters, except that the highest median of nitrate was found in Group B. Furthermore, statistically significant differences among the climatic groups were detected in the means and medians of the concentrations for all the nutrient species in both the ANOVA and Kruskal–Wallis tests. The means of metal concentrations were not significantly different among the climatic groups in the ANOVA test, whereas their medians were significantly different among the climatic groups in the Kruskal–Wallis test. Provided that rain water and ambient environment introduce low-to-negligible amounts of pollutants, Figure 4 demonstrates the leaching of these pollutants from green roofs.

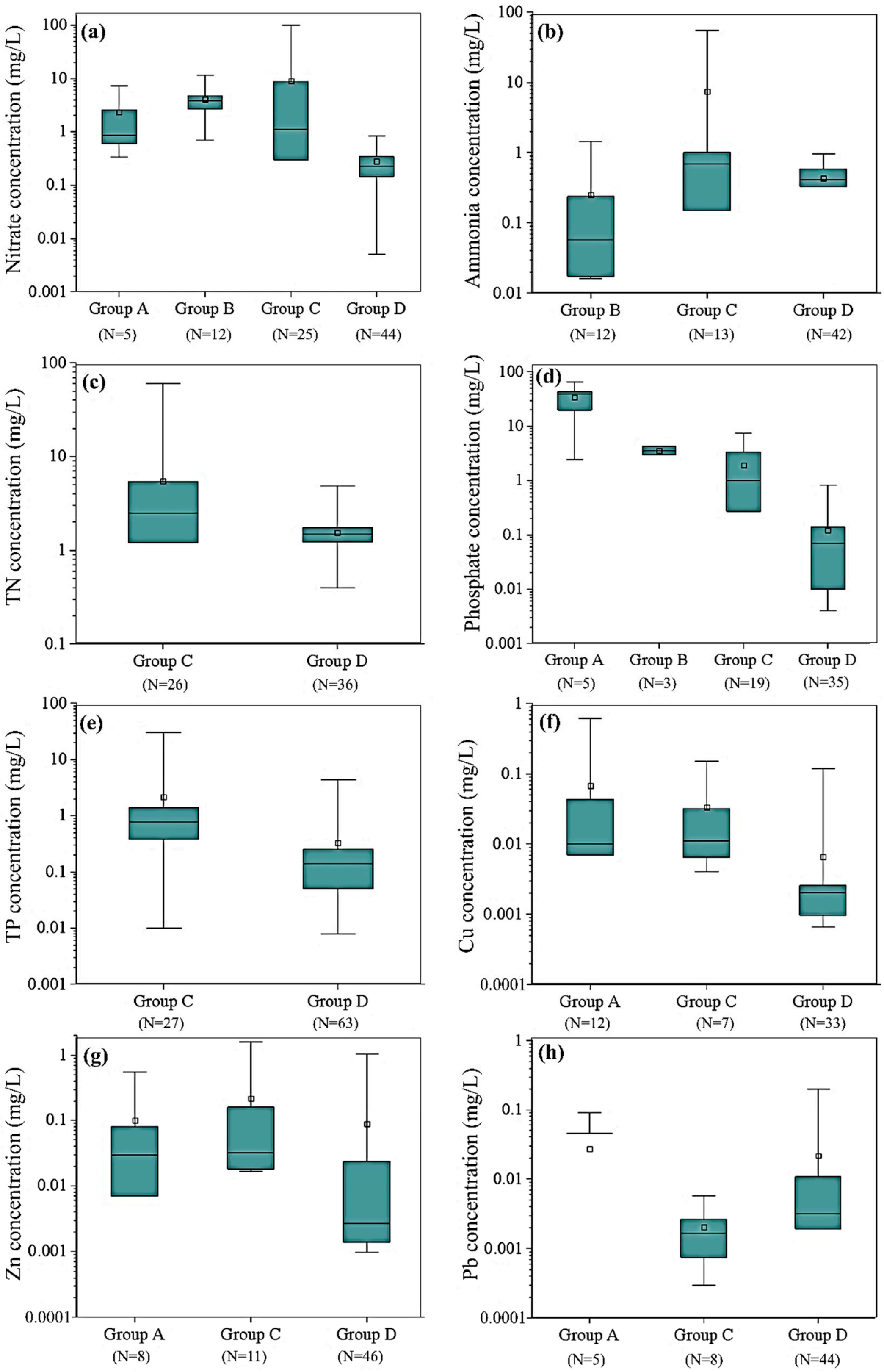

Figure 4. Box-whisker plots of green roof outflow concentrations of (**a**) nitrate, (**b**) ammonia, (**c**) total nitrate (TN), (**d**) phosphate, (**e**) total phosphorus (TP), (**f**) Cu, (**g**) Zn, and (**h**) Pb in primary climatic groups, respectively. The box covers the range of data between the 25th and 75th percentiles; the whiskers extend to the minimum and maximum values; the median and mean are indicated by the line and the square inside the box, respectively; N is the sample size.

5.2. Influence of Design Variables on Water Quality

5.2.1. Growing Media Composition

As discussed previously, the selection of the growing media largely depends on the local availability of materials, and thus, the growing media used largely varied among the primary climatic groups and within a climatic group (Table A1). Because the tendencies to retain or release various pollutants are the function of the physical and chemical properties of the growing media, the water quality behavior of a green roof is primarily determined by the growing media [111]. The high cation exchange capacity and high internal surface areas of zeolite increased water and nutrient storage [112], for example, while the sand component of the growing media tended to lose a substantial amount of ammonium compared with the clay media, because sands have a large particle surface area [111]. A study conducted regarding Group A [21] argued that water quality concentrations (metals and inorganic ions) of green roof outflow strongly depended on the chemical properties of the growing media (such as adsorption capacity and chemical composition). A study by Wang et al. concerning Group D [81] obtained similar results for nutrients (nitrogen and phosphorus). Wang et al. [81] also recommended the use of commercial media rather than local media, which could contain high levels of humus and inorganic fertilizers, to reduce nutrient leaching.

The addition of organic matter, which is primarily for supporting vegetation establishment and growth, could promote nutrient leaching. Generally, the addition of organic matter such as compost increases the cation exchange capacity of the growing media and, thus, can enhance nutrient storage. Despite this advantage of organic matter, its amount should be kept low, as decomposed organic materials can leach and, thus, contribute to the degradation of outflow water quality by elevating nutrient concentrations and coloration. This was demonstrated in many studies conducted concerning Group C and Group D. Several studies regarding Group C [10,11] and Group D [5,12] revealed that the release of nutrients from green roofs resulted from the addition of compost to the growing media during the establishment and maintenance periods. Additionally, the application of fertilizers to the green roofs was found to elevate the nutrient concentrations, such as the TN and TP concentrations in Group C [31] and high phosphorus concentrations in Group D [69]. Furthermore, the leaching of metals (Pb and Zn) from green roofs constructed using Arkalyte (an expanded clay) mixed with pine bark was observed in a study in Group D [79]. In contrast to the effect of the addition of organic matter on water quality, the addition of soil amendments has been suggested to reduce/or prevent water soluble nutrients from leaching. Biochar was found to be effective in reducing the discharge of nutrients in a study investigating green roofs in Portland, OR, USA, in Group D [113]. However, another study conducted in Lahti, Finland (Group D) [114], did not observe consistently the effect of biochar in reducing the nutrient concentrations. The inconsistent results on the role of biochar in reducing nutrient leaching might be explained by the fact that the properties of biochar can vary considerably, and thus, some biochar might be unfavorable for this purpose [111,114].

Different compositions of the growing media (primary and secondary compositions), which are used for different purposes and have different physical and chemical properties, affect the behavior of the chemical constituents in green roofs differently. Additionally, the growing media used in green roofs vary largely in the primary climatic groups and within the individual primary groups. Thus, it is very complicated to qualitatively and quantitatively link the water quality concentrations to the growing media. Overall, this review revealed that the addition of organic matter (mainly for vegetation) in many implementations of green roofs promotes nutrient leaching, while the use of soil amendments, such as biochar, has the potential to reduce/prevent nutrient leaching, but the large variation of their properties might challenge their application. These have been demonstrated in studies conducted regarding Group C and/or Group D, while the knowledge might be transferable to other climatic groups. To avoid the unintended consequence of the implementation of green roofs (namely producing pollution), the addition of organic matter and amendment to the growing media, which are added for different purposes, should be optimized to prevent water quality degradation of green roof outflow, as these two additives play opposite roles in nutrient leaching.

5.2.2. Growing Media Depth

Figure 5 displays the box-whisker plot of growing media depth in the primary climate groups except Group B, for which the information was unavailable. Note that this figure is similar to Figure 2a, but it depicts the media depth of the green roofs for reviewing the water quality of their outflow. The means and medians of the media depths were significantly different among the groups. In particular, the media depth in Group A was statistically higher than those in Group C and Group D, while the growing media depths of Group C and Group D were statistically similar, as they had similar means, medians, and variation ranges. When comparing Group C with Group D, the concentrations of all water quality parameters (except Pb) in Group C were significantly higher than those in Group D. Conversely, when comparing Group A with Group C, the means and medians of water quality concentrations in Group A were statistically higher than (such as phosphate and Pb), or similar (such as nitrate, Cu) to those in Group C. Therefore, these results generally support that the growing media depth does not primarily affect the water quality of the green roof outflow. In individual studies, inconsistent or contradictory results for the association of water quality and media depth were reported. A field study conducted in China (Group D) [81] concluded that the increase in depth was beneficial to reducing nutrient concentrations, because a greater media depth could retain nutrients for longer durations and increase the chance for them to be consumed. Note that in the above study, the dual media layers, namely the absorption layer placed below the nutrient layer, were applied, and, overall, the green roofs acted as a sink for pollution. Alternatively, another study conducted in Adelaide, Australia (Group C) [58], concluded that thinner growing media resulted in less pollutant leaching (when green roofs behaved as a source of pollution) by comparing extensive and intensive green roofs. The observed inconsistent effects of the growing media depth on water quality might be due to the minor role of the media depth compared with other influential factors (the growing media composition, for example). Furthermore, the effect of the media depth on nutrients could vary among different species, as different relationships between their concentrations and the media depth were reported, for example, from a green roof study conducted in Paris, France (Group C) [44].

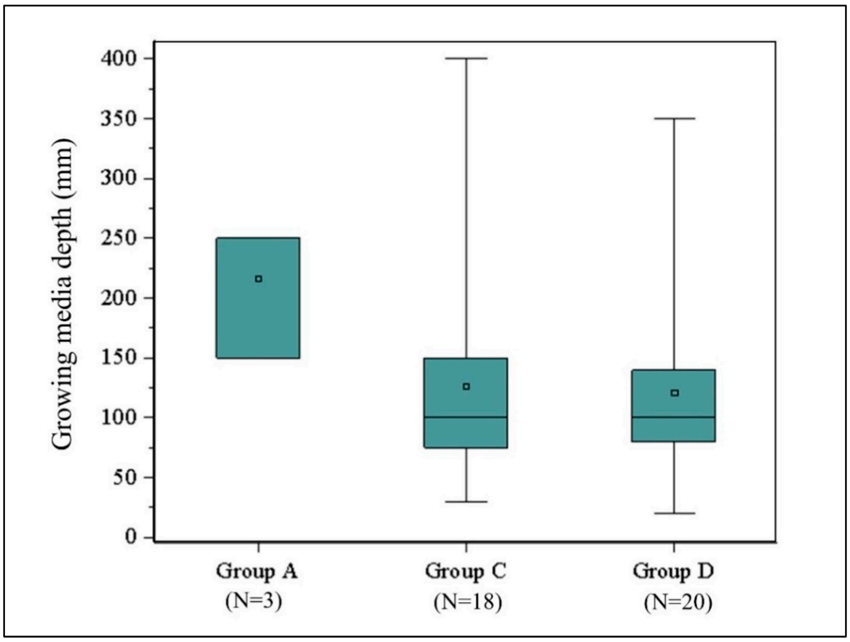

Figure 5. Box-whisker plots of growing media depth in the primary climatic groups, respectively. The box covers the range of data between the 25th and 75th percentiles; the whiskers extend to the minimum and maximum values; the median and mean are indicated by the line and the square inside the box, respectively; N is the sample size.

5.2.3. Vegetation

The type of vegetation used can also impact the water quality of the green roof outflow, as the need for nutrients by vegetation varies from one species to another. This was demonstrated in a study by Aitkenhead-Peterson et al. [115] that detected differences in nitrate and phosphate concentrations in green roof outflow among green roofs, which were vegetated with three types of plants (*Sedum kamtschaticum*, *Delosperma cooperi*, and *Talinum calycinum*) on the same growing media in Texas, USA (Group C). This study observed the lowest nutrient concentrations from the green roof vegetated by *Delosperma cooperi*, with the highest nutrient concentrations from the green roof planted with *Sedum kamtschaticum*. Another study by Monterusso et al. [69] regarding Group D concluded that the green roof planted with herbaceous vegetation was more efficient in reducing nitrate concentration than that vegetated with *sedum* species, whereas noticeable differences in phosphorus concentration were not observed. Conversely, some researchers [13,116,117] promoted the use of diverse plant communities rather than monoculture vegetation, as nutrients were used more efficiently by diverse plant communities. Overall, the above studies consistently argued the inferior efficiency of *sedum* in reducing nutrient concentrations compared with other vegetation types. Figure 6 displays the percentages of the vegetation types used in the reviewed green roofs in the primary climatic groups, respectively. As illustrated in this figure, *sedums* were the most commonly used vegetation in all climatic groups (except Group A), although *sedums* have been shown to be inferior in reducing nutrients compared with other types of vegetation. The common use of *sedums* in the climatic groups might be due to its high survival ability and the low maintenance required.

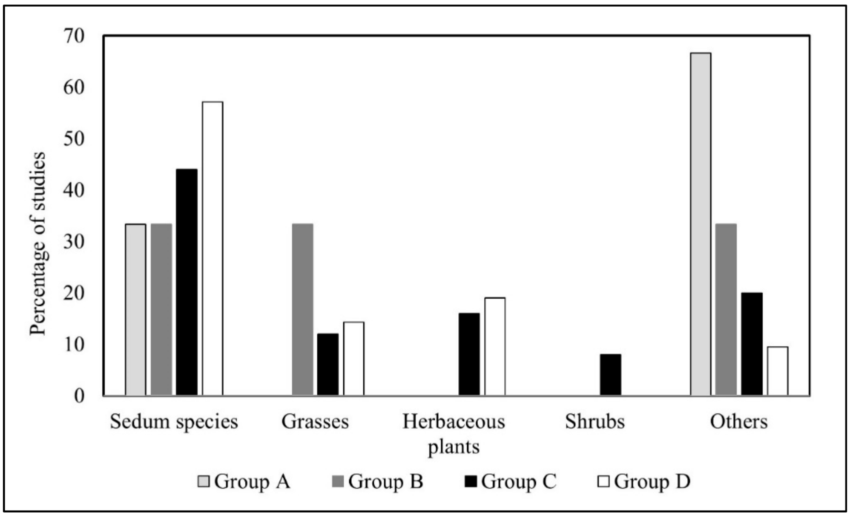

Figure 6. The percentages of the green roofs vegetated with *sedum* species, grasses, herbaceous plants, shrubs, and others in the four primary climatic groups, respectively.

5.3. Influence of Hydrologic Variables on Water Quality

Similar to the hydrologic behavior of green roofs, hydrologic variables, especially rainfall characteristics and antecedent dry weather period (ADWP), are believed to affect the water quality behavior of green roofs. Rainfall volume has been recognized as one of the important factors affecting nitrogen and phosphorus leaching [13], and it might also affect other dissolved constituents. However, very limited research has been conducted to investigate the association between water quality concentrations and rainfall characteristics. Teemusk and Mander [12], who investigated this topic to a very limited extent, observed that heavy rain elevated concentrations of TP and phosphates in green roof outflow. Other hydrologic variables, such as ADWP, are also revealed to be associated with the water quality behavior of green roofs. Seidl et al. [44] observed that green roofs situated in Paris, France (Group C), acted as a sink for nitrogen, phosphorus, zinc, and copper in small rain events when the medium was principally dry, whereas they were a source of pollutants, especially for phosphorus. Note that in small rain events, especially after dry periods, the retention capacity of green roofs and, thus, their stormwater retention rate are expected to be high. The low discharge of pollutants might link with the high hydrologic performance of green roofs in small events. Concerning both pilot- and field-scale green roofs, their antecedent condition (such as antecedent soil moisture (ASM) or ADWP) and the magnitude of rain events (natural or simulated) vary from one study to another and from one event to another. Thus, in the quantification and comparison of water quality performances of green roofs, without explicitly considering the differences in these influential hydrologic variables, the results would be biased. Furthermore, the characterization of rainfall (such as amount, intensity, and duration) and ADWP in the primary climatic groups might help achieve further understanding of their roles in different climatic groups.

6. Conclusions

This review paper synthesized and compared the hydrologic and water quality performance of green roofs among the four primary climatic groups (A, B, C, and D). The comparison results, in particular, between Group C and Group D, in which significant differences in the water quality concentrations were detected, suggested that green roofs behave differently in different climatic groups. The large spread of the design and hydrologic variables among the primary climatic groups and between two sub-climatic groups in Group C, as well as the inconsistent results (green roof performance) reported in the existing studies, were observed. All these might hinder the translation of knowledge among different primary climatic groups and among sub-climatic groups. The lack of studies for climatic Group A and Group B also call for the need to examine green roof performance in these two climatic groups to implement this technology more confidently.

Furthermore, an investigation was conducted to explore what factors would primarily contribute to the performance differences among green roofs. The effects of potential influential factors, including design variables (growing media composition and depth, roof slope, and vegetation type) and hydrologic variables (rainfall and ADWP), were examined. Among these design variables, the growing media was believed to be the most important factor influencing both the hydrologic and water quality behavior of the green roofs, although the association between the green roof performance and the growing media was not qualitatively and quantitatively identified in this review. The establishment of the direct linkage of the green roof performance and the growing media would be highly challenging as the selection of growing media appears to be primarily dependent on the local availability of materials, which leads to the use of a variety of media in green roofs. Additionally, other design variables (media depth, roof slope, and vegetation type) were observed to affect the water quality of the green roof outflow to a certain degree and possibly were inconsistent among the climatic groups and within a climatic group. Moreover, the potential effects of hydrologic variables were identified as well. Overall, this review revealed that the behavior of green roofs is affected by multiple design and hydrologic variables, which challenges the design of "optimal" green roofs to meet the service level required for stormwater management. Regarding green roof design, it is recommended to quantitatively identify the most influential variables, which might principally vary among the climatic groups. Thus, their design can be conducted primarily considering these variables to implement green roofs more widely and with confidence.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Summary of the hydrologic performance of green roofs and the water quality concentrations of their outflow along with design variables in the reviewed studies classified into different climatic groups.

Reference	Sub-Climatic Group (b)	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) (c)	TN (mg/L) (c)	Nitrate (mg/L) (c)	Ammonia (mg/L) (c)	TP (mg/L) (c)	Phosphate (mg/L) (c)	Cu (mg/L) (c)	Zn (mg/L) (c)	Pb (mg/L) (c)
Group A: Tropical (megathermal) climate															
[16] Qin et al. (2012)	–	NTU, Singapore	8.50	250	Flowering plants (cuphea) and grasses	n/a	11.40	n/a (d)	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[17] Musa et al. (2008)	–	Parit Raja, Johor, Malaysia	6.00	200	Pearl grass	n/a	16.70–47.90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[18] Kasmin and Musa (2012)	–	Parit Raja, Johor, Malaysia	0.00	150	Pearl Grass	1: 3: 5 of sand: burn soil: and red soil	33.00–100.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[19] Kasmin et al. (2014)	–	Kuala Lumpur, Malaysia	n/a	n/a	n/a	n/a	51.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[20] Kok et al. (2016)	–	Kuala Lumpur, Malaysia	35.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2.40	n/a	n/a	n/a
[21] Vijayaraghavan et al. (2012)	–	NTU, Singapore.	6.99	150	Sedum species	White peat, black peat and clay; natural inorganic volcanic material, compost, organic and inorganic fertilizers	n/a	n/a	0.34–0.86	n/a	n/a	19.80,40.00	0.037, 0.056	n/a	0.00
[22] Vijayaraghavan and Raja (2015)	–	IIT Madras, India	6.99	250	Flowering plant (P. grandiflora)	Perlite, vermiculite, sand, crushed brick, coco-peat and Sargassum biomass	n/a	n/a	n/a	n/a	n/a	n/a	0.00–0.01	0.006–0.041	0.00
[23] Vijayaraghavan and Joshi (2014)	–	IIT Madras, India	6.99	250	Flowering plant (P. grandiflora)	Red soil, clay, sand and cow manure; vermiculite, perlite, sand, crushed brick and coco-peat.	n/a	n/a	n/a	n/a	n/a	n/a	.004–0.61	0.02–0.56	0.00–0.09
[24] Alberta Ingenuity 2008	–	Calgary, AB, Canada (a)	4.00	150	Grasses (sheep fescue, blue grama, and june grasses)	Recycled content 68% and 74% by weight.	59.00, 66.00	n/a	1.12,4.00	0.82,1.45	n/a	2.94,4.20	n/a	n/a	n/a

Table A1. *Cont.*

Reference	Sub-Climatic Group [b]	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) [c]	TN (mg/L) [c]	Nitrate (mg/L) [c]	Ammonia (mg/L) [c]	TP (mg/L) [c]	Phosphate (mg/L) [c]	Cu (mg/L) [c]	Zn (mg/L) [c]	Pb (mg/L) [c]
Group B: Dry (arid and semiarid) climate															
[25] Dabbaghian (2014)	–	Kelowna, BC, Canada [a]	5.24	n/a	Sedum species and succulents (delosperma)	lightweight, mineral based materials	n/a	n/a	0.69–11.59	0.016–0.20	n/a	n/a	n/a	n/a	n/a
[26] Sims et al. (2016)	–	Calgary, AB, Canada [a]	0, 21.00	150	Sedum species	Fine and coarse haydite, crushed dolostone, bark, peat moss, and some fertilizer.	61.10–75.20	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Group C: Temperate climate															
[7] Moran et al. (2003)	Cfa	Kinston, NC, USA	5.00	102	Sedum species and succulents (delosperma)	n/a	63.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Cfa	Goldsboro, NC, USA	minimal	102, 51	Sedum species and succulents (delosperma)	n/a	62.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[27] Moran et al. (2005)	Cfa	Goldsboro, NC, USA	n/a	75	n/a	n/a	63.00	0.80-6.80	n/a	n/a	0.60–1.50	n/a	n/a	n/a	n/a
	Cfa	Raleigh, NC, USA	n/a	100	n/a	n/a	55.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[8] Hathaway et al. (2008)	Cfa	Goldsboro, NC, USA	0.00	75, 100	Sedum species and succulents (delosperma)	Perma till (Stalite 3/8 in. expanded slate), sand, composted cow manure	64.00,64.00	0.70–6.90	n/a	n/a	0.60–1.40	n/a	n/a	n/a	n/a
[28] Palla et al. (2011)	Cfa	Genoa, Italy	n/a	200	n/a	n/a	68.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[29] Fioretti et al. (2010)	Cfa	Northwest and Central Italy	n/a	350	Shrubs (broom) and herbaceous plants (lavender and rosemary)	Lapillus, pumice, zeolite, and 200 l/m3 of peat	68.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[30] Gnecco et al. (2013)	Cfa	Genoa, Italy	n/a	200	Grass	lapillus, pumice, zeolite, peat	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.032	n/a
[31] Toland et al. (2012)	Cfa	Fayetteville, Arkansas, USA	n/a	n/a	Sedum species	Straw, cow manure, and chicken litter	n/a	0.72–1.88	0.17–0.41	0.13–0.18	0.17, 2.03	0.14–1.82	n/a	n/a	n/a
[32] Malcolm et al. (2014)	Cfa	Norfolk, VA, USA	4.00	100	Sedum species	Expanded slate and compost	n/a	1.37–3.33	n/a	n/a	0.33–0.70	n/a	0.024	0.037	n/a

Table A1. *Cont.*

Reference	Sub-Climatic Group [b]	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) [c]	TN (mg/L) [c]	Nitrate (mg/L) [c]	Ammonia (mg/L) [c]	TP (mg/L) [c]	Phosphate (mg/L) [c]	Cu (mg/L) [c]	Zn (mg/L) [c]	Pb (mg/L) [c]
[33] Buffam et al. (2016)	Cfa	Cincinnati, OH, USA	36.40	100	Sedum species	Tremco's standard aggregate-based extensive green roof substrate,	n/a	n/a	0.00–10.20	0.00–0.70	n/a	1.00–3.40	n/a	0.56	n/a
[34] Hsiao and Chen (2012)	Cfa	Taipei City, Taiwan	n/a	n/a	Herbaceous and Sedum species	sandy loam/expanded clay/vermiculite/waste cotton/peat soil	n/a	n/a	9.01	0.22	0.01	n/a	n/a	n/a	n/a
[35] Chen and Kang (2016)	Cfa	Taipei City, Taiwan	n/a	100	Creeper forb, sedum, flowering plant (*Sansevieria trifasciata*) and shrubs (aloe)	Recycled fiber and pottery stone	n/a	1.22, 10.37	n/a	n/a	1.96-3.00	n/a	n/a	n/a	n/a
[36] Carson et al. (2013)	Cfa	NY, USA	n/a	32, 100	Sedum species and native	n/a	36.00–61.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[37] Carpenter et al. (2016)	Cfa	Syracuse, NY, USA	1.00, 15.00	102	Sedum species	Lightweight growth media.	96.80	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[9] Hakimdavar et al. (2014)	Cfa	NY, USA	n/a	32	n/a	n/a	32.00–85.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[38] Mendez et al. (2011)	Cfa	Austin, TX, USA	2.00	n/a	n/a	n/a	n/a	n/a	0.00–4.70	n/a	n/a	n/a	n/a	0.018–0.362	0.0003–0.0058
[39] Harper et al. (2015)	Cfa	Rolla, MO, USA	n/a	102	Sedum species	Arkalyte mix	40.00, 60.00	>60.00, 10.00	n/a	n/a	>30.00, 5.00	n/a	n/a	n/a	n/a
[40] Simmons et al. (2008)	Cfa	Austin, TX, USA	n/a	100	Native perennial plants	Expanded shale/clay, vermiculite, sand, organic matter	8.00-88.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[41] Carter and Rasmussen (2006)	Cfa	Athens, GA, USA	2.00	76	Sedum species and succulents (delosperma)	Stalite expanded slate, sand, and composted organic matter	78.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[42] Nardini et al. (2012)	Cfa	Basovizza, Trieste, Italy	n/a	120, 200	Herbaceous plants and shrubs	Lapillus, pomix, zeolite, and peat	63.00–90.00.	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[11] Berndtsson et al. (2009)	Cfa	Fukuoka, Japan	n/a	400	70 differentplant species. Leaves, trees, and bushes	Perlite, siliceous rock; aqua soil	n/a	0.59	0.11	0.15	0.01	0.00	n/a	n/a	0.001, 0.003
	Cfb	Malmö, Sweden	n/a	30	sedum-moss	Crushed lava, natural calcareous soil, clay, and shredded peat, organic content	n/a	2.31	0.07	0.08	0.31	0.27	0.149–0.032	n/a	n/a

Table A1. *Cont.*

Reference	Sub-Climatic Group [b]	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) [c]	TN (mg/L) [c]	Nitrate (mg/L) [c]	Ammonia (mg/L) [c]	TP (mg/L) [c]	Phosphate (mg/L) [c]	Cu (mg/L) [c]	Zn (mg/L) [c]	Pb (mg/L) [c]
[43] Gromaire et al. (2013)	Cfb	Trappes, Paris, France	n/a	30, 150	Sedum species and grasses	Natural pumice, lava, bark compost and green compost, organic matter	n/a	0.80–1.80	n/a	n/a	0.38–0.78	n/a	n/a	n/a	n/a
[44] Seidl et al. (2013)	Cfb	Paris, France	n/a	60, 160	Sedum species	volcanic rock (pozzolan), bark and peat, organic matter	n/a	n/a	1.10; 1.10	n/a	n/a	3.80; 6.00	0.011,0.010	0.017, 0.017	n/a
[4] Fassman-Beck et al. (2013)	Cfb	Auckland, New Zealand	n/a	50–150	Sedum species	Volcanic pumice, composted pine bark fines; pumice, expanded clay and compost-based.	45.00–92.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[45] Voyde et al. (2010)	Cfb	Auckland, New Zealand	n/a	50, 70	Sedum species	Pumice, zeolite, and expanded clay, all pumice based.	72.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[3] Stovin et al. (2012)	Cfb	Sheffield, UK	2.75	80	Sedum species	Crushed brick and fines.	42.74	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[46] Stovin (2010)	Cfb	Sheffield, UK	2.75	n/a	Sedum species	Crushed bricks and fine	34.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[47] Speak et al. (2013)	Cfb	Manchester, UK	n/a	170	n/a	n/a	65.70	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[1] Nawaz et al. (2015)	Cfb	Leeds, UK	2.00	Extensive	Sedum species	n/a	66.21	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[48] Liesecke (1998)	Cfb	Hannover-Herrenhausen, Germany	2.00	20–120	n/a	n/a	40.00–60.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[49] Dürr (1995)	Cfb	Germany	minimal	25–101	Mosses, sedum, grasses, and herbaceous plants	n/a	58.00–71.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[50] Franzaring et al. (2016)	Cfb	Hohenheim, Germany	0.00	120	Sedum species, grasses, herbaceous plant, and shrub.	Crushed bricks, clayey slate, compost and peat	40.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[51] Bengtsson et al. (2005)	Cfb	Malmo, Sweden	2.60	30	Sedum species and mosses	Clay, crushed limestone, crushed roof tiles, sand, and organic material.	46.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Table A1. *Cont.*

Reference	Sub-Climatic Group [(b)]	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) [(c)]	TN (mg/L) [(c)]	Nitrate (mg/L) [(c)]	Ammonia (mg/L) [(c)]	TP (mg/L) [(c)]	Phosphate (mg/L) [(c)]	Cu (mg/L) [(c)]	Zn (mg/L) [(c)]	Pb (mg/L) [(c)]
[52] Villarreal and Bengtsson (2005)	Cfb	Lund, Sweden	3.50–25.00	40	Sedum species	Crushed limestone, crushed brick, sand, clay, and organic material.	10.00–62.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[53] Arias et al. (2016)	Cfb	Mions, France	0.00	60	Sedum species	n/a	38.00–72.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[54] Perez et al. (2016)	Cfb	Bogotá, Colombia	1.00	n/a	Sedum species, native vegetables (radish, lettuce), grass, flowering plant bergenia, herbaceous plant lavender	n/a	63.50–89.90	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[55] Johnston et al. (2004)	Cfb	Vancouver, BC, Canada	n/a	350, 200	Grasses (Elijiah Blue, Blue Fescue, Green Fescue) and shrubs (Kinnikinnick)	n/a	48.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[56] Connelly et al. (2006)	Cfb	Vancouver, BC, Canada	2.00	75, 150	Sedum species and grasses (*Festuca scoparia*, *Bouteloua gracilis*, and *Carex glauca*)	White pumice, sand and organic compost	6.00–100.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[57] Berkompas et al. (2008)	Csb	Seattle, WA, USA	n/a	150	n/a	n/a	30.50	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			n/a	100–125	n/a	n/a	33.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			n/a	150	n/a	n/a	17.10	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[58] Razzaghmanesh et al. (2014a)	Csb	Adelaide, SouthAustralia	n/a	n/a	Succulent (*Carpobrotus rossii*), grasses (*Lomandra longifolia Tanika*), herb (*Dianella caerulea Breeze*), and shrub (*yoporum parvifofium*)	Crushed brick, scoria, coir fiber, and composted organics; scoria, composted pine bark, and hydro-cell flakes	n/a	n/a	6.11–21.27	n/a	n/a	0.36–1.54	0.004–0.0064	0.0168–0.0231	0.0005–0.0012
[59] Beecham and Razzaghmanesh (2015)	Csb	Adelaide, South Australia	1.00, 25.00	100, 300	Herbaceous plants	Red crushed brick, scoria, coir fiber, and composted organics; comprised scoria, composted pine bark, and hydro-cell flakes	51.00,96.00	n/a	1.00–100.00	1.00–20.00	n/a	0.03–7.50	n/a	n/a	n/a

Table A1. *Cont.*

Reference	Sub-Climatic Group (b)	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) (c)	TN (mg/L) (c)	Nitrate (mg/L) (c)	Ammonia (mg/L) (c)	TP (mg/L) (c)	Phosphate (mg/L) (c)	Cu (mg/L) (c)	Zn (mg/L) (c)	Pb (mg/L) (c)
Group D: Continental climates															
[5] Bliss et al. (2009)	–	Pittsburg, PA, USA	n/a	140	Sedum species	Expanded shale, perlite, and coconut husk.	70.00	0.00	n/a	n/a	2.00–3.00	n/a	n/a	0.02	0.20
[60] Morgan et al. (2012)	–	IL, USA	n/a	50–200	Sedum species	Arkalyte and composted pine bark.	50.00	n/a	3.00–70.30	n/a	n/a	n/a	n/a	n/a	n/a
[61] Berghage et al. (2010)	–	Chicago, IL, USA	n/a	76	n/a	n/a	74.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[62] Hutchinson et al. (2003)	–	Portland, OR, USA	minimal	110	Succulents, grasses and herbaceous species	n/a	69.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[63] Kurtz (2008)	–	Portland, OR, USA	n/a	125	n/a	n/a	56.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	–	Portland, OR, USA	n/a	75	n/a	n/a	64.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[64] Spolek (2008)	–	Portland, OR, USA	n/a	100–150	Flowering plants	n/a	12.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			n/a	150	Sedum, Bunchgrass	n/a	25.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			n/a	100–150	Grasses	n/a	17.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[65] Rowe et al. (2003)	–	East Lansing, MI, USA	6.50	40,60	Sedum species	n/a	69.00, 72.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[66] Whittinghill et al. (2015)	–	East Lansing, MI, USA	2.00	105	Sedum species, native vegetable and herbaceous species	Extremely coarse sand, very coarse sand, coarse sand, medium sand, fine sand, very find sand, extremely fine sand, silt, clay	58.00–98.00	n/a	0.04–0.30	n/a	0.02, 0.44	n/a	n/a	n/a	n/a
[67] Russell and Schickedantz, (2003)	–	Dearborn, MI, USA	2.00	20,100	Sedum species and native	n/a	39.00, 58.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[68] VanWoert et al. (2005)	–	MI, USA	2.00, 6.50	25, 40, 60	Sedum species	Heat-expanded slate, peat, dolomite, composted yard waste and composted poultry litter by volume	60.60–70.70	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[69] Monterusso et al. (2004)	–	MI, USA	2.00	20, 60	Sedum species	Heat-expanded slate, grade sand, aged compost, peat	38.60–58.10	n/a	n/a	n/a	0.00046–0.00439	n/a	n/a	n/a	n/a

Table A1. *Cont.*

Reference	Sub-Climatic Group [(b)]	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) [(c)]	TN (mg/L) [(c)]	Nitrate (mg/L) [(c)]	Ammonia (mg/L) [(c)]	TP (mg/L) [(c)]	Phosphate (mg/L) [(c)]	Cu (mg/L) [(c)]	Zn (mg/L) [(c)]	Pb (mg/L) [(c)]
[3] Carpenter and Kaluvakolanu (2011)	–	MI, USA	n/a	101.6	sedum species	Lightweight expanded shale blend, organic matter	84.46	n/a	0.69	n/a	0.63	n/a	n/a	n/a	n/a
[70] Getter et al. (2007)	–	MI, USA	2.00, 7.00, 15.00,25.00	60	Flowering plant and sedum species	Sand 91.18% Silt 5.60% and Clay 3.22%.	80.80	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[71] DeNardo et al. (2005)	–	Philadelphia, PA, USA	0.00	89	Sedum species	n/a	19.00–98.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[72] Gregoire and Clausen (2011)	–	Storrs, CT, USA	n/a	102	Sedum species.	Lightweight expanded shale, composted biosolids, and perlite.	51.40	0.49	nitrate+nitrite: 0.369	0.023	0.043	0.025	0.006	0.011	n/a
[73] Liu and Minor (2005)	–	Toronto, ON, Canada	minimal	75, 100	Sedum species	Lightweight, granules.	57.00	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[6] TRCA (2006)	–	Toronto, ON, Canada	10.00	140	Non-native grasses and herbaceous flowering plants (forbs)	n/a	65.30	n/a	0.033-0.710	0.001–0.089	0.062–0.936	0.0459–0.8091	0.0095, 0.119	0.0021–0.0137	0.0025–0.0115
[74] Van Seters et al. (2009)	–	Toronto, ON, Canada	10.00	140	Non-native grasses and herbaceous flowering plants (forbs)	Crushed volcanic rock, compost, blonde peat, cooked clay, and washed sand.	39.00–85.00	n/a	0.11, 0.23	0.00-0.02,	0.23–0.45	0.16–0.36	0.0335–0.0595	0.0054–0.0088	0.00
[26] Sims et al. (2016)	–	London, ON, Canada	21.25.	150	Sedum species	Fine and coarse haydite, crushed dolostone, bark, peat moss, and some fertilizer.	76.50	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[26] Sims et al. (2016)	–	Halifax, NS, Canada	21.25	150	Sedum species	Fine and coarse haydite, crushed dolostone, bark, peat moss, and some fertilizer.	59.60	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[75] Berghage et al. (2009)	–	PA, USA	n/a	90–100	Sedum species	Expanded clay with some compost amendment	52.60	n/a	n/a	n/a	0.41	n/a	n/a	n/a	n/a
[76] Teemusk and Mander (2011)	–	Tartu, Estonia		70–200	Sedum acre, grass (Gramineae species), flowering plant (*Thlaspi arvense*)	Lightweight aggregate, humus and clay	n/a	0.40–4.90	0.005–0.85	0.01–0.30	0.008–0.69	0.004–0.64	n/a	n/a	n/a

Table A1. *Cont.*

Reference	Sub-Climatic Group [b]	Study Location	Roof Slope (%)	Media Depth (mm)	Vegetation Type	Growing Media Composition	Stormwater Retention Rate (%) [c]	TN (mg/L) [c]	Nitrate (mg/L) [c]	Ammonia (mg/L) [c]	TP (mg/L) [c]	Phosphate (mg/L) [c]	Cu (mg/L) [c]	Zn (mg/L) [c]	Pb (mg/L) [c]
[12] Teemusk and Mander (2007)	–	Tartu, Estonia	0.00	100	Sedum species, herbaceous flowering plants (forbs)	LWA, humus and clay	85.70	1.20–2.10	0.42–0.8	0.12–0.33	0.026–0.09	0.006–0.066	n/a	n/a	n/a
[77] Krebs et al. (2016)	–	Lahti, southern Finland	8.00	60–70	Mosses, sedum species, herbs, and grasses	Crushed brick, compost, peat and crushed bark.	50.52	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[78] Lee et al. (2015)	–	Seoul, Korea	0.00	100–150	Sedum species	Volcanic materials and soil with peat moss (50 mm), perlite	13.80–60.80	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[79] Alsup et al. (2011)	–	IL, USA	n/a	50–200	Sedum species	Fine Arkalyte and composted pine bark	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.0235–1.0536	00102–0.1354
[80] Yang et al. (2015)	–	Beijing, China	n/a	150	Sedum species	n/a	78.27	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
[81] Wang et al. (2013)	–	Tianjin, China	5.24	100–350	Sedum species	Perlite and vermiculite mixed (1:1)	n/a	1.64–1.98	n/a	0.46–0.59	0.35–0.49	n/a	n/a	n/a	n/a
[82] Wang et al. (2017)	–	Tianjin, China	3.50	100	Sedum species	Pumice, activated charcoal, zeolite, Lava, Perlite, vermiculite	33.80–65.90	1.01–1.94	0.11–0.53	0.32–0.94	0.02–0.25	0.01–0.24	0.00066–0.00271	0.00097–0.00324	0.00137–0.00376

[a] The City of Calgary and Kelowna, Canada, are classified into Group D based on the Koppen–Geiger climate classification; whereas, they have been considered to have a semi-arid climate in studies, for example [26] Sims et al. (2016) and [25] Dabbaghian (2014). Therefore, they were classified into Group B in this review paper; [b] This review paper also compared the sub-climatic groups Cfa and Cfb for the primary climatic Group C. Thus, the sub-climatic groups (Cfa, Cfb, and Csb) for the primary group C were included into the table; [c] For a study, in general, the ranges (from minimum to maximum) of stormwater retention rate and water quality concentrations of outflow were reported. The measured/calculated numbers can be derived from different rainfall events, growing media depths, roof slopes, etc. Note the average numbers (e.g., average green roofs of different growing media depths and/or roof slopes) were also reported in some studies, for which the average numbers were reported in the table. However, the reported numbers obtained from all field and/or experimental runs in a study were used in the statistical analysis of the paper; [d] Not available (n/a).

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