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Review

Exploring Influencing Factors and Innovative Solutions for Sustainable Water Management on Green Roofs: A Systematic Quantitative Review

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Abstract: Green roofs are becoming popular in urban areas due to their potential benefits, including energy efficiency, urban heat island mitigation, and stormwater management. However, their water consumption can negatively impact water resources. Therefore, carefully managing the water consumption of green roofs is crucial to ensure they do not exacerbate existing water scarcity issues. This review explores the influencing factors and innovative solutions that increase the sustainability of water management on green roofs. A systematic quantitative review was conducted on published studies on green roofs. The review highlighted that while small-scale experimental studies are almost saturated, large-scale monitoring studies are still lacking. Modelling and assessing green roof settings based on climatic conditions and water availability and consumption are essential for successful water management. Using integrated technologies and sensing systems can increase water management efficiency and sustainability. Rainwater may be sufficient as a water source for green roofs in wet climates, while irrigation is still needed in other climates. Phytoremediation and biosorption can potentially increase runoff water quality. Improving hydrological performance by increasing rainwater retention and reducing water consumption capacity can reduce demand for other water resources and effectively manage small storms, mitigating pressure on city infrastructure and increasing water quality. Seeking non-potable sources, such as greywater, or harvesting enough rainwater to be used for irrigation during dry weather periods is highly advantageous for improving the sustainability of green roofs.

Keywords: green roofs; runoff quantity; runoff quality; irrigation; water consumption; water management

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1. Introduction

Green roofs are gaining popularity as a sustainable technology in urban areas due to their potential to provide numerous benefits, including energy efficiency, urban heat island mitigation, and occupant health and wellbeing [1,2]. In addition, they are considered adequate as key components of many promising rainwater management strategies [3–7]. Green roofs can retain rainwater and reduce and delay runoff, which is essential in urban areas where solid surfaces replace permeable surfaces, leading to inefficient stormwater management and potential infrastructure damage [3–10]. Solid surfaces reduce the likelihood of water infiltration, evapotranspiration, or proper runoff treatment, which becomes more problematic in areas with extreme precipitation due to global warming [9,11,12]. Therefore, implementing green roofs in a built-up environment can serve as a promising stormwater management strategy and an urban green infrastructure, allowing them to restore the natural balance of urban water cycles [13,14].

However, the negative impact that the water consumption of green roofs may have on water resources is a concern [15–17]. During periods of drought or in regions with limited water resources, the water consumption of green roofs can become a significant issue and may affect other water uses, such as agriculture, industry, and residential needs [15–17]. Therefore, it is essential to carefully manage the water consumption of green roofs to ensure they do not exacerbate existing water scarcity issues.

Green roofs can be classified as intensive or extensive based on their minimum and maximum depths [18]. They usually consist of several layers, including a vegetation layer, substrate layer, filter layer, drainage layer, protection mat, and root barrier, which play an essential role in their hydrological performance [19] (Figure 1). However, the water storage capacity of these layers is limited, with the primary water storage located inside the substrate, in addition to a retained amount in the drainage layer and the plants [1,20]. Improving the hydrological performance of green roofs by increasing their rainwater retention and reducing their water consumption capacity can provide several benefits, including reducing the demand for other water resources, effectively managing small storms, mitigating the pressure put on city infrastructure, and increasing water quality [7,9,12,20,21].

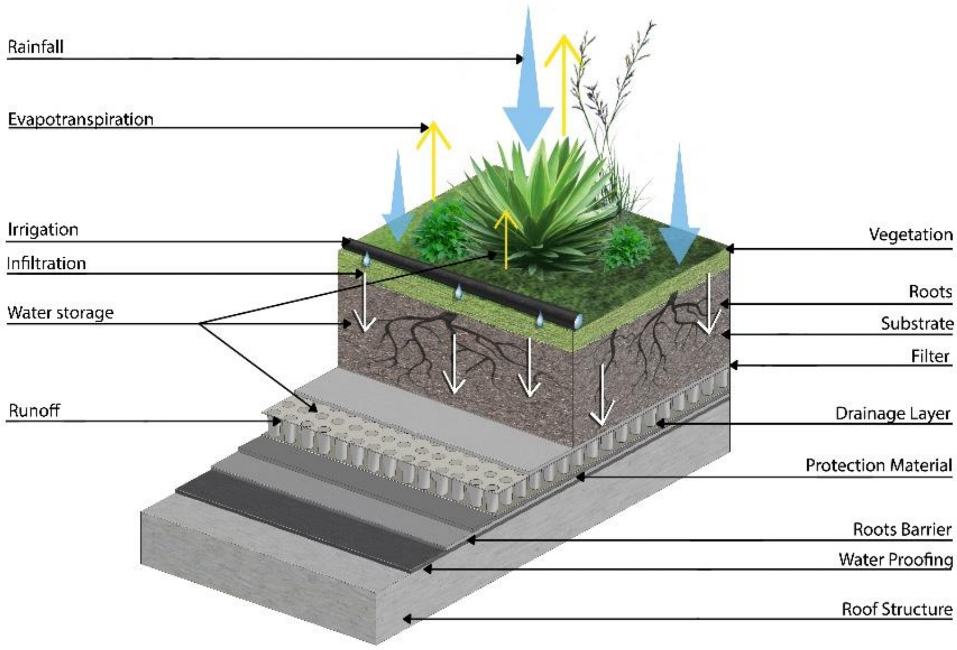


Figure 1. Typical green roof layers and their hydrological processes (drawn by the author based on the description provided by Vesuviano and Stovin [19]).

Despite numerous studies on different aspects of green roofs, a comprehensive review of the capacity of green roofs to sustainably manage water on them and the relevant influencing factors is lacking. Therefore, this review aims to explore the influencing factors and innovative solutions that increase the sustainability of water management on green roofs. To achieve this, the study has systematically investigated published studies on green roofs, focusing on the following questions:

a. Question 1: What is the impact of green roofs on runoff quantity and quality, and what are the key controlling factors?
b. Question 2: What are the water retention and consumption capacities of green roofs, and what are their influencing factors?
c. Question 3: Which design aspects can be altered, and what techniques can be employed to improve the sustainability of water management on green roofs?

2. Background about Water Sources and Their Quality

The water sources on green roofs can be either rainwater or irrigation. The following subsections explain these sources and their quality.

2.1. Rainwater

Following current sustainable practices, rainwater is considered the primary source of water on green roofs in wet climates and a secondary source in dry climates [22]. Rainwater is classified as a non-polluted source [23]. However, rainwater discharges pollutants accumulated in the atmosphere from anthropogenic air pollution [24], reducing its quality. Rainwater can be acidic and contain large amounts of nitrates and traces of other pollutants, such as heavy metals and pesticides, depending on the local pollution sources and winds [9,25]. The measurements of pollutants proved this during and after rain events. These studies show that the air contains significantly less pollution than before a rainfall event [24]. Contaminated water will flow into the substrate layer and aggregate the pollution burden, which will further influence the next runoff quality due to the large number of pollutants held back within the substrate layer [9,26,27]. Therefore, air quality significantly affects rainwater quality.

2.2. Irrigation

Irrigation is the primary water source for green infrastructure in dry climates and a secondary source in wet climates [22]. The water for irrigation can be from several sources with different qualities. These sources are classified in national and international standards [28] as (1) non-polluted (groundwater, municipal water, and harvested rainwater/runoff) and (2) polluted (stormwater, surface water/water bodies, greywater and treated wastewater) [23,29] sources. These sources differ substantially in their quality. Groundwater and municipal water are high-quality sources, although the latter may act as a source of chloride [30]. Stormwater differs from harvested runoff [11] by combining rainwater from different surfaces, such as roads, sidewalks, and roofs. It may include a significant quantity of pollutants [31], such as suspended solids, toxic metals, petroleum hydrocarbons, pathogenic bacteria, and increased turbidity values [29,32,33]. In some cases, it may even contain sewage because intense rainfall can lead to the flooding of the urban sewage infrastructure [9]. Water bodies (e.g., rivers, lakes, springs, swamps, creeks, lagoons, and other natural watercourses) [34] may be polluted from stormwater runoff, animal faecal material, or sewage effluent [29]. Finally, greywater from a building's different activities, such as baths, showers, hand basins [14,35], and treated wastewater, may contain nitrogen, phosphorus, and various nutrients or other contamination [27,36]. Using greywater and wastewater requires unique methods and configurations for green roofs.

3. Methodology

The systematic quantitative literature review method, initially proposed by Pickering and Byrne [37], can help researchers analyse and summarise the academic literature related to a specific topic. This method allows for a comprehensive overview of the field and can help identify research gaps. This approach is not selective or limited to the expertise of the authors, unlike traditional narrative reviews, and can be easily replicated, with the results remaining consistent when the procedure is repeated.

The systematic quantitative literature review protocol for the current study consisted of three main stages. First, the keywords relevant to the research topic and the specific research questions were identified. Second was the structuring of the new database, which involved establishing and testing the structure of the new database, including the selection criteria, analytical categories, and revision processes. Finally, all the relevant papers were fed into the newly constructed database and analysed. One significant drawback of this systematic quantitative literature review method is that it relied solely on online searches to gather articles, limiting the review to online articles written in English. This means that studies only available in print or other languages may not be included in the review.

According to Pickering and Byrne [37], using a mix of databases is recommended, as it increases the comprehensiveness of the research and favours the triangulation of the results. Therefore, the Scopus and Web of Science databases were used, as they were the most relevant to the research topic. The databases were searched for published articles between 1 January 2009 and 15 December 2019 and then regularly updated until 2 April 2023.

To explore the influencing factors and innovative solutions for sustainable water management on green roofs, the primary search term used was 'green roof*', combined with various keywords related to the research topic (Table 1). The search included the literature titles and keywords. As the first criterion, repeated and off-topic research was excluded, which resulted in 439 papers. To ensure the originality of the research, as the second criterion, only peer-reviewed literature published in scholarly journals was included, and only research papers published between 2009 and 2023 were selected. In addition, the papers retained that only focused on the hydrological performance of green roofs or sustainable water management and those that solely mentioned the keywords but did not address them in the research were excluded, which resulted in 374 articles. However, only some are referenced as part of the bibliography of this review. For a complete list of the selected papers, please refer to the Supplementary File.

Table 1. Keywords used for the research in this study.

Hydrological Performance	Water Sources	Water Quality	Water Management	Innovative and Integrated Solutions
Green roof* runoff	Green roof* *water	Green roof* *water quality	Green roof* *water manag*	Green roof* integrated technolog*
Green roof* retention	Green roof* irrigat*	Green roof* *water pollut*	Green roof* *water harvest*	Green roof* integrated infrastructure
Green roof* drought*	Green roof* *water source*	Green roof* runoff quality	Green roof* *water design*	Blue green roof*
Green roof* drain*	Green roof* precipitation	Green roof* runoff pollut*		Constructed wetland roof*
Green roof* storm*	Green roof* rain*	Green roof* runoff contaminat*		
Green roof* hydrolog*		Green roof* *water treat*		

Note: Any word containing the root word signalled by * is also part of the set. For example, 'manag*' includes the words 'managing' and 'management'.

To answer the research questions, the literature was systematically reviewed, assessing (i) who conducted the research, (ii) when it was conducted, (iii) the geographical distribution of the research, (iv) the journal discipline, and (v) the patterns or relationships found in the research. A thematic data analysis was conducted using a text-mining process to understand the influencing factors and innovative solutions for sustainable water management on green roofs. The text-mining process was utilised in two stages. The first considered the hydrological performance of green roofs, focusing on water quantity management, while the second stage focused on water quality management. The predominant research topics were identified using the text of the journal abstracts in the first phase. Then, Leximancer was used to analyse their content, extract primary information, and identify the main concepts. Leximancer is a tool that can analyse documents and identify important concepts. It uses advanced models and interactive visuals to provide valuable insights and practical ideas. Additionally, it conducts sentiment analysis without bias [38]. The last step included thoroughly reading the related sections and summarising and reporting the results.

4. Statistical Results

The research areas were distributed into 30 categories and dominated by environmental sciences ecology (63%). Before applying the selection criteria, the initial research resulted in 1148 published research papers (Figure 2), while the selected papers were 374 journal articles (Supplementary Material).

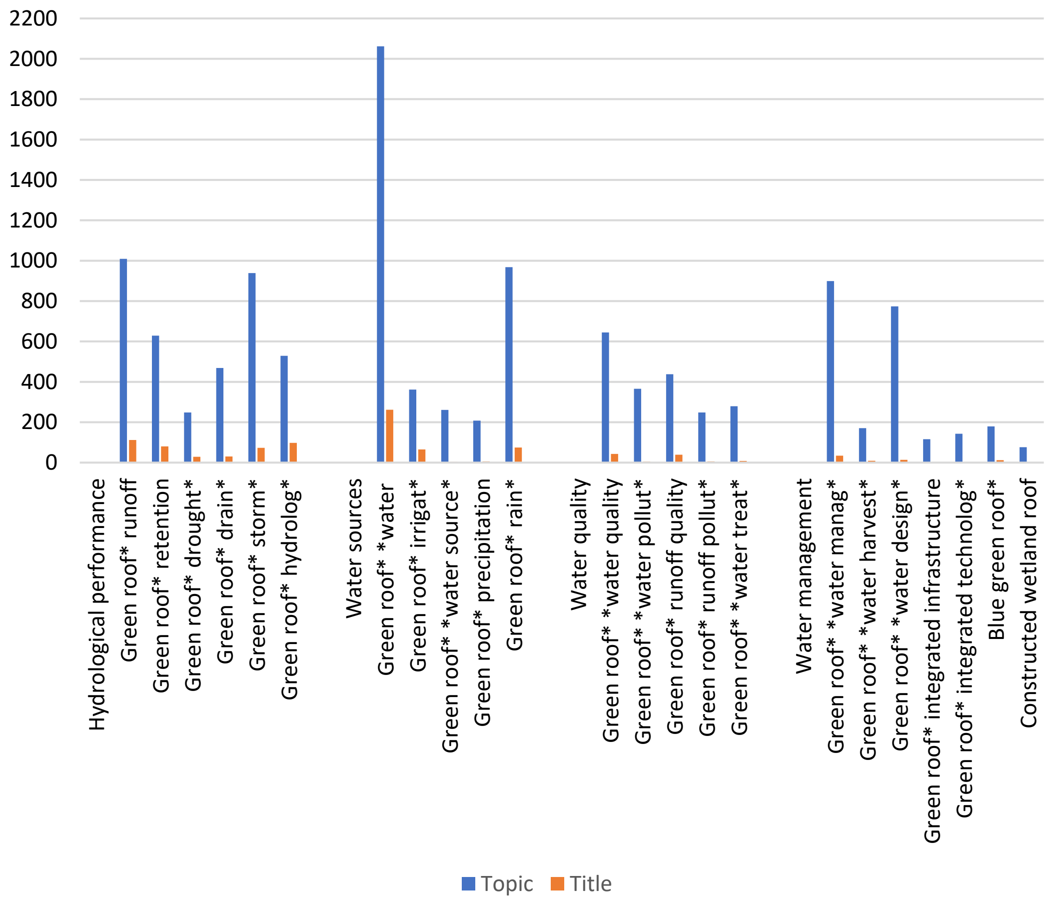


Figure 2. Initial research results before filtering, updated on 2 April 2023. Note: Any word containing the root word signalled by * is also part of the set.

The selected articles were from 102 different journals. The Journal of Ecological Engineering published the most on this topic (11%), followed by the Journal of Water (9%) (see Figure 3A). The United States of America and China were the most interested countries regarding the hydrological performance of green roofs, publishing 78 and 74 articles, respectively (Figure 3C). The authors C. Farrell and V. Stovin were the most published on this topic. They published 16 and 12 papers, respectively (Figure 3D). The published research in this area escalated through the investigated years, except 2017, 2019, and 2022, and reached the maximum in 2021 with 48 articles (Figure 3B). It should be noted that 2023 was included up to early April. However, compared with the same period in 2021, the number of published articles was slightly higher, which reflects the continuously escalating interest in this research area.

Based on the text-mining analysis of the results (Figures 4 and 5A), rainwater was investigated significantly more than any other water resource, and few studies investigated irrigation. The rainwater investigations focused on water retention capacity and the ability to reduce runoff. Various climate characteristics, such as weather conditions and rainfall events, as well as roof construction elements and layers, were identified as the factors that most influenced the amount of water retained on green roofs. These main findings helped categorise the papers found and structure the results section. Although intensive green roofs are more capable of water management, extensive green roofs were investigated four times more often than intensive ones. Out of the different elements of the green roof structure, the substrate was the most investigated layer, with studies evaluating its effect on water retention and consumption by selecting different plant species, drainage layers, and roof slopes. Sedum was the most frequently examined plant species because of its tolerance to dry weather periods and its limited need for additional irrigation.

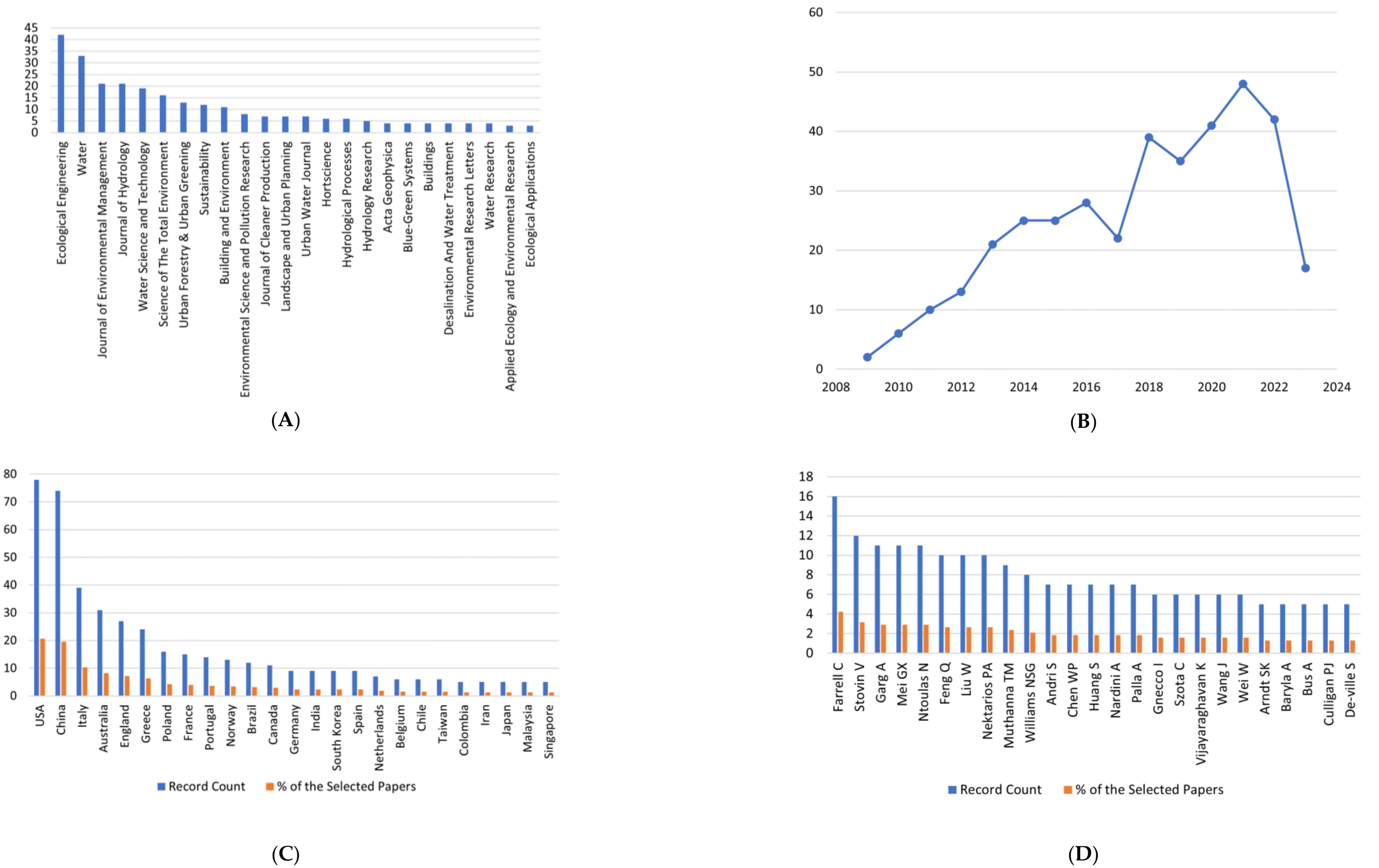


Figure 3. Statistical results from the selected articles in this review between 1 January 2009 and 2 April 2023. (**A**) The journals where the highest number of articles on this topic were published; (**B**) the number of articles published each year that were investigated; (**C**) the countries where most of the research was conducted; and (**D**) the authors who published the most on this topic.

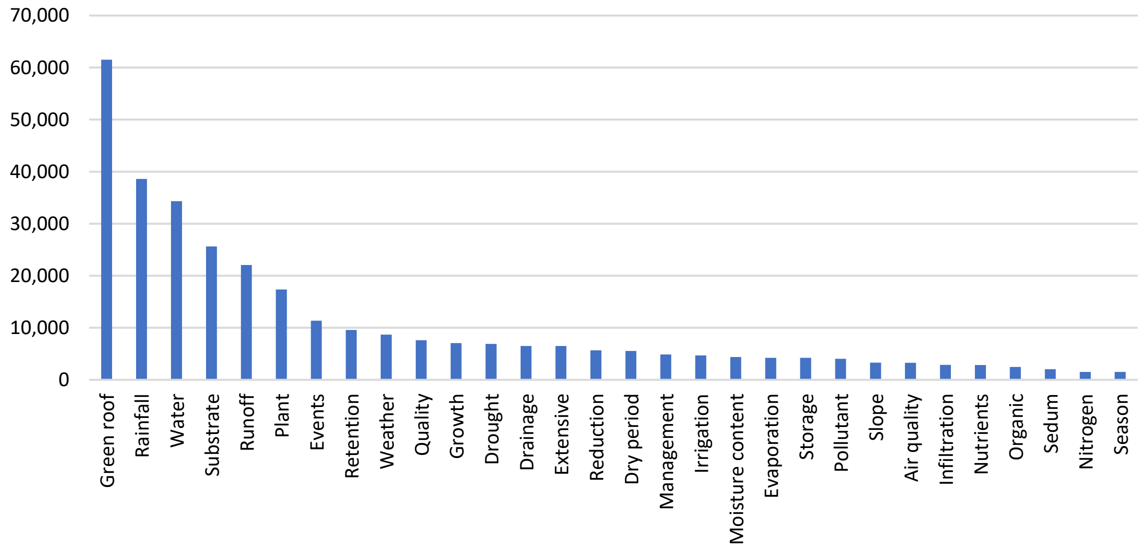
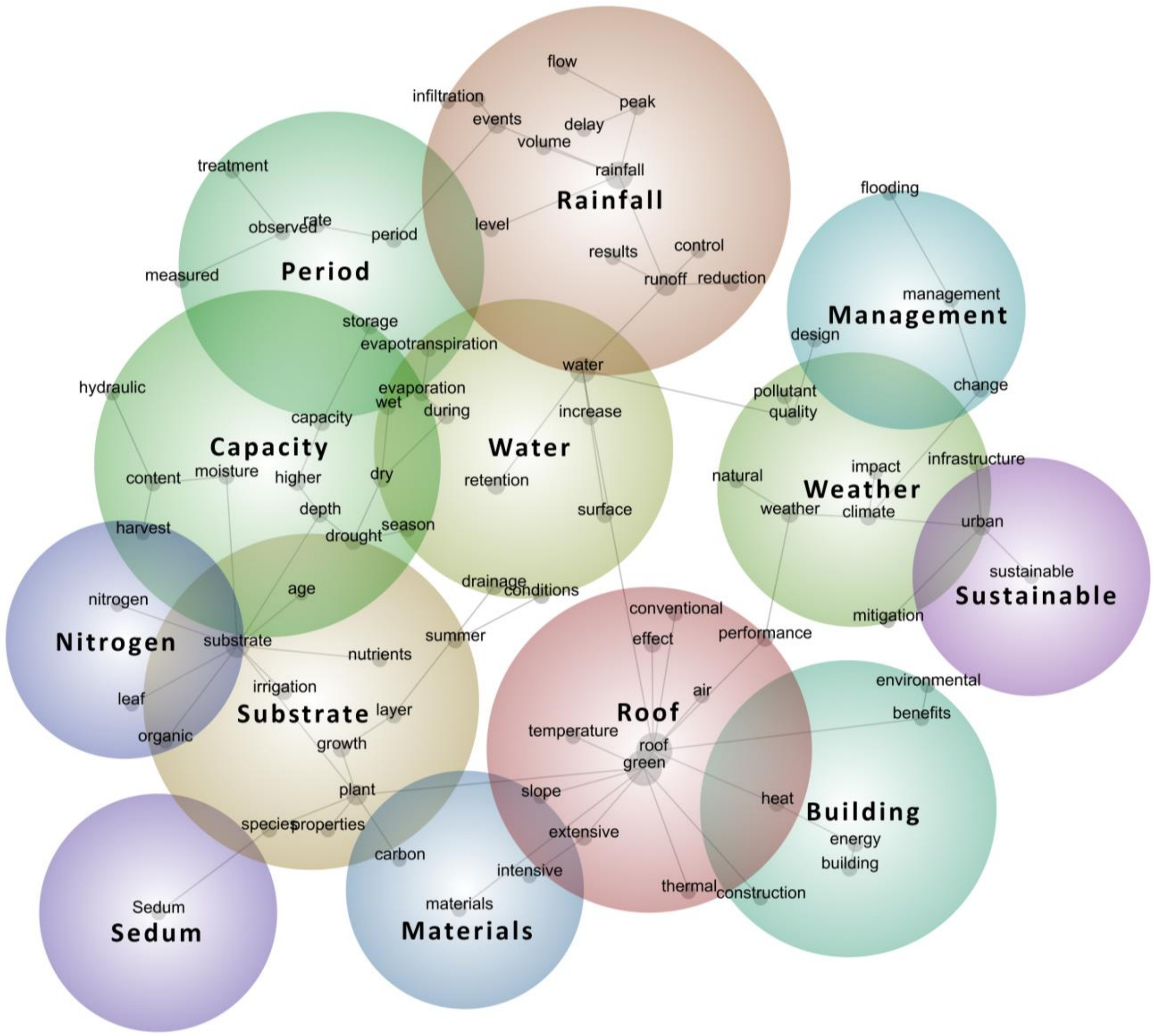
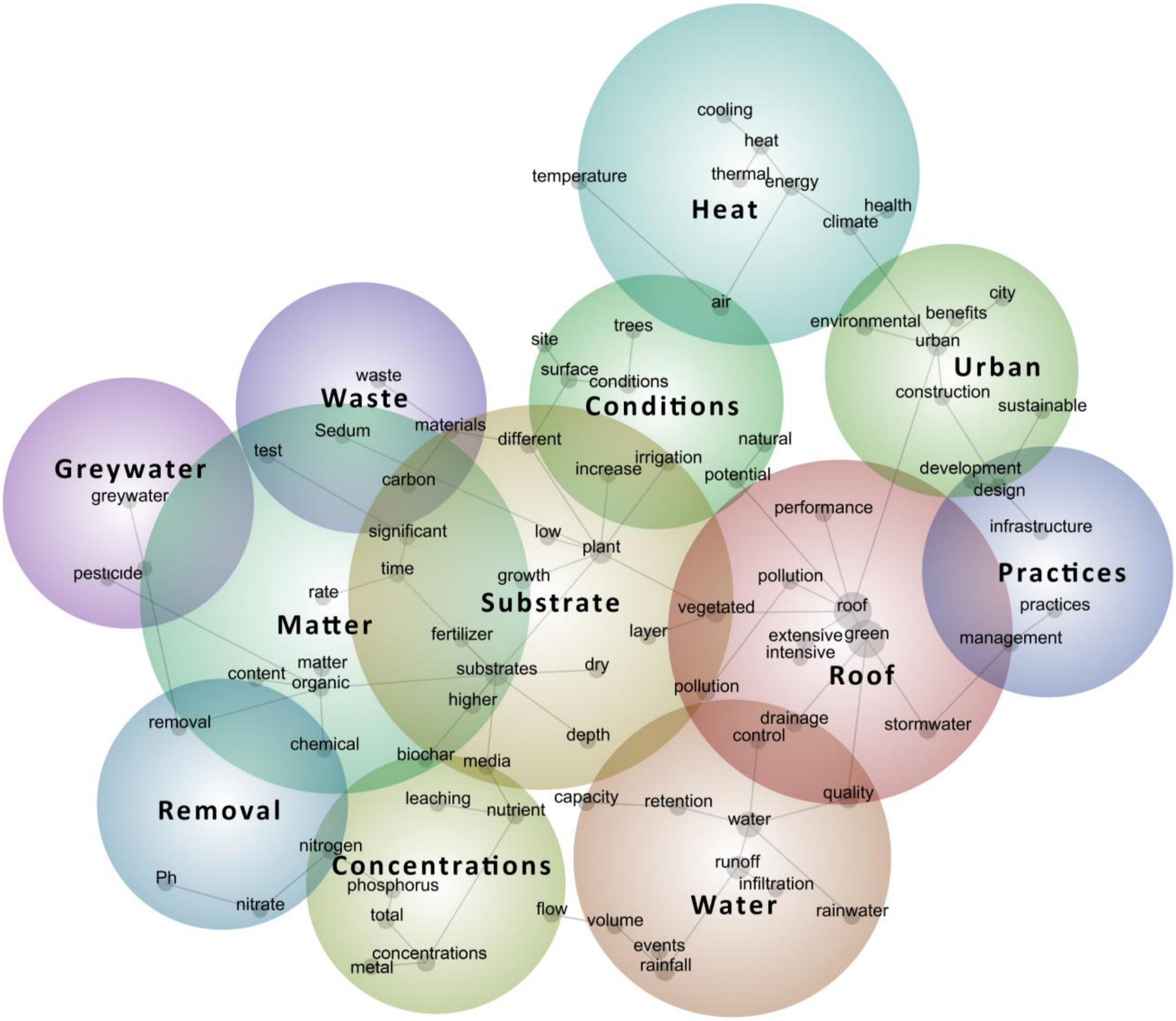


Figure 4. Most common keywords in the analysed literature related to the review topic.



(A)

Figure 5. *Cont.*



(**B**)

Figure 5. Concept map produced by Leximancer for the investigated literature. (**A**) Papers that target water quantity and (**B**) papers that target water quality. The size of a theme (bubble) indicates the number of keywords related to that theme. The bigger the bubble, the more keywords it represents. The colour of the theme ranges from red, orange, light green, dark green, blue, and purple. This colour scale represents the frequency of keyword repetition, with red indicating the highest frequency and purple indicating the lowest.

According to the analysis of the results from the text mining in the second stage (Figures 4 and 5B), previous research efforts focused on two main research directions: rainwater runoff quality and alternative water sources for irrigation. Extensive green roofs were three times more often researched for the context of water quality on green roofs than intensive systems, and the substrate and planting layers received more attention than the drainage layer. The substrate investigations were mainly concentrated on substrate depth or the mixture of materials and their ability to retain or release different pollutants, such as organic matter, metals, and nutrients. The plant investigations focused on the effects of different species and their growth related to water quality, including their ability to reduce the concentrations of different pollutants in the soil. Drainage layers were investigated as pollutant sources in drainage water. Other studies emphasised chemical pollutants from pesticides and fertilisers, the surrounding environment, and green roof surfaces. Less research focused on the ability of green roofs to treat waste and greywater and the effect of the retained pollutants from this treatment on runoff water.

5. The Impact of Green Roofs on Runoff Quantity

5.1. Rainwater Retention

The capacity of a green roof to retain water influences its ability to reduce runoff and mitigate stormwater [7,39,40]. Most studies on the water retention of green roofs worldwide base their assessment on the percentage of rainfall harvested by a green roof over a specific period [20]. Generally, the average water retention capacity of a green roof ranges between 8% and 100% based on the climate and the green roof type and configuration [12,28,41–46], making it difficult to compare, as the numerical values vary across most studies [9]. For instance, Li and Yeung [47] reported that green roofs can retain water produced by any small rain event with a volume of less than 10 mm and can demonstrate a variety of runoff results, ranging from 26% to 88%. In contrast, Simmons and Gardiner [46] observed capacities ranging between 8% and 88% on different green roofs, and Burszta-Adamiak and Abdef [48] stated that the water retention rate for 153 rainfall events reached 82.5% and almost 100% in low-capacity events [48]. Table 2 summarises the selected examinations of the water retention capacity of green roofs across different settings and climates to explain their influence on the hydrological performance of green roofs.

Table 2. Selected investigations on the rainwater retention of various green roof settings in different climates. RWR = rainwater retention.

Reference	Methods	Climate	Location	Green Roof Type	Green Roof Area (m^2)	Rainfall Depth (mm)	Rainfall Events	Substrate Depth (cm)	RWR Rate (%)
Li and Liu [49]	Experiment	humid subtropical	Chongqing, China	Test beds	1.44	2.26–71.20	99	20	40–83
Todorov, Driscoll [50]	Measurements	Cool, humid	Syracuse, NY, USA	Extensive	1190	6.93 ± 6.50 average	-	9.5	75–99.6
Soulis, Ntoulas [43]	Experiment	Mediterranean	Athens, Greece	30 test beds	2	10.3 average	-	8 and 16	50.6–81.1
Brandao, Cameira [42]	Experiment	Mediterranean	Lisbon, Portugal	Test beds	2.5	13.05 average	184	15	71.1–82
Zhang, Miao [51]	Experiment	Subtropical, monsoon	Chongqing, China	Test bed	1	1116.5 total	19	15	35.5–100
Beecham and Razzaghmanesh [28]	Experiment	Hot, Mediterranean	Adelaide, Australia	16 test beds	0.15	24.12 average	5	10 and 30	52 and 95
Burszta-Adamiak [52]	Experiment	Temperate	Wroclaw, Poland	Five test plots	2.88	-	153	-	82.6–99.9
Simmons, Gardiner [46]	Experiment	Subhumid, subtropical	Austin, TX, USA	24 roof platforms	3.4	89.3 total	3	10	8–88
Stovin, Dunnett [41]	Experiment	Temperate	Sheffield, UK	Test bed	3	9.2 average	11	8	10–90
Carter and Rasmussen [53]	Experiment	Humid, subtropical	Athens, GA, USA	Test plot	42.64	1079 total	31	7.62	39–100
VanWoert, Rowe [40]	Experiment	Temperate	MI, USA	Vegetated roof	5.9536	-	-	2.5	60.6–96

5.2. Delaying the Peak Runoff

Green roofs can experience runoff under certain conditions, such as during heavy rainfall or when the green roof substrate becomes saturated [54]. The rainwater retention feature of green roofs provides an opportunity to delay and reduce peak flows, specifically in frequent storms of smaller magnitudes [55]; this can help control the volume of stormwater. Many studies have reported delays in the runoff after rain events of a smaller intensity on green roofs [56,57]. However, their records contain vast differences due to the various green roof settings, environments, and investigated climates. For example, Getter and Rowe [10] studied 12 extensive green roof platforms with 4 different slopes (2%, 7%, 15%, and 25%) and observed marginal delays for all the studied platforms. By contrast, DeNardo and Jarrett [58] noticed delays in the start of the runoff on a green roof by an average of 5.7 h under an average rainfall intensity of 4.3 mm/hour. Therefore, rainfall characteristics and green roof settings significantly affect the delay time (peak to peak). However, it is challenging to draw a conclusion about the required green roof settings for the best performance from the reviewed articles, and a case-by-case assessment is needed, which will be presented in the discussion section. Lastly, the runoff delay increases with the increase in the rainwater retention ability of a green roof. Table 3 summarises the selected investigations of the peak delay of the runoff of different green roof types and climates.

5.3. Influencing Factors

The water retention abilities of green roofs vary widely, and the current literature has conflicting results. This is mainly due to the various settings of green roofs and the climate in which they are situated and is an indication of the complexity of assessing their hydrological performance [12,28,41–46]. This section summarises the most important factors that influence the water balance in green roofs.

Table 3. Important papers on the peak delay of runoff waters in different green roof settings and climates.

Reference	Method	Climate	Location	Substrate Depth (cm)	Plants	Delay Runoff (h)
Wang, Garg [59]	Experiment + modelling	tropical	South China	10, 19, 25	Grass	0.40–1.68
Santos, Silva [54]	Experiment	Mediterranean	Lisbon, Portugal	15	*Sedum album*, *Sedum sexangular*, *Sedum spurium*, *Sedum spurium tricolor*, *Sedum coral reef*, *Sedum oreganum*, *Sedum forsteriamum*, *Armeria Maritima* and *Thymus red creeping e Rosmarinus officinalis*.	0.03–0.30
Zhang, Lin [60]	Experiment	humid continental	Beijing, China	10, 15	*Sedum* spp.	1.05–2.18, 1.36–3.50
Brandao, Cameira [42]	Experiment	Mediterranean	Lisbon, Portugal	15	Mixed Shrubs, grass, and moss Grass (*Brachypodium phoenicoides*) Shrub (*Rosmarinus officinalis*) Bare soil	0.49 2.54 1.26 0.94
Burszta-Adamiak, Stańczyk [61]	Experiment	Temperate	Wroclaw, Poland	extensive green roof	*Sedum acre*, *Sempervivum*	1.5–1.7
Almaaitah and Joksimovic [62]	Experiment	continental climate	Toronto, ON, Canada	25–30	Planted with seeds of thirty different crops	7.70–8.00
Carter and Rasmussen [53]	Experiment	Humid, Subtropical	Athens, GA, USA	7.62	*Sedum* spp.	0.58
Nawaz, McDonald [63]	Measurements	Maritime, temperate	Leeds, UK	3	*Sedum* spp.	4.25–8.25

5.3.1. Climate Characteristics

Each climate has a different influence on the hydrological performance of a green roof, and its overall impact cannot be predicted or measured because each climate has different trends across different regions. In general, rainfall events, dry weather periods, and seasons were all found to be important factors in the assessment of rainwater retention in green roofs. Rainfall depth and intensity have a strong negative correlation with the water retention rate [21,39,64,65], and as they decrease, the retention rate increases [10,40,46,50,65,66]. Local weather patterns and seasonal conditions influence the soil moisture content [20,67,68]. For instance, a dry weather period is crucial for hosting rainwater, as it allows for evapotranspiration (ET) and vegetation water consumption to reduce the soil moisture content and increase the retention ability in the next rainfall [20,63,65,67,68]. Different climatic conditions cause variations in dry weather periods; therefore, their relationship with the green roof retention capacity must be characterised [3,39,44,45,69]. Different seasons also affect the capacity of a green roof to retain rainwater throughout the year and exhibit different retention rates [63,64,66]. Although the water retention percentage greatly depends on the rainfall input, it is not the only controlling factor [70]. The retention capacity of a green roof is finite and can be maximised only up to the maximum water-holding capacity of the green roof [3,39,50,58], which is dependent on the factors discussed in the following subsections.

5.3.2. Substrate Characteristics

The water storage capacity of the substrate mostly depends on the growing medium composition, depth, and maximum water-holding capacity [20,40,58,71–73]. An increase in substrate depth has been shown to improve water retention performance in green roofs [4,40,43,73]. The composition of the substrate is also an essential variable affecting its water-holding capacity [74]; for instance, coarser materials retain less rainwater [75]. Some papers have introduced new material compositions to increase the substrate's water-holding capacity. For instance, Vijayaraghavan and Raja [57] proposed a mixture of expanded perlite, coco peat, exfoliated vermiculite, crushed bricks, and sand with a particle size ranging between 0.25 mm and 4 mm, which showed a water-holding capacity of 39.4% [57]. Several researchers also suggested the addition of gritty loam soil, perlite-based substrates, foam sheets, fibreglass, and biological additives, such as seaweed and hydrophilic gels, for the same aim [22,76]. A few examples are summarised in Table 4.

Table 4. Selected articles on different substrate properties and their effects on runoff. WHC = water holding capacity, and RWR = rainwater retention.

Article	Substrate Depth	Max WHC%	Growing Media Composition	RWR Rate (%)
Beecham and Razzaghmanesh [28]	10 30	41	(A) Crushed red brick, scoria, coir fibre, and composted organics	70 74
	10 30	44	(B) Comprised scoria, composted pine bark, and hydro-cell flakes	58 60
	10 30	48	(C) 50% of media type B with 50% organic compost	68 70
Simmons, Gardiner [46]	10	34	(A) Expanded shale, sand, and organic matter	21.67
		37	(B) Expanded clay, expanded shale, sand, and organic matter	51.67
		43	(C) Expanded clay, sand, perlite, and organic matter	41.67
		46	(D) Decomposed granite, perlite, and organic matter	58.33
		38	(E) Expanded clay, expanded shale, sand, and organic matter	32
		32	(F) Expanded clay, expanded shale, sand, and organic matter	17
Baryla, Karczmarczyk [77]	8	20	Washed gravel	62.7
	8	20	Expanded clay aggregate	62.7
	17	55	Washed sand, chalcedony, clay, low peat, and compost	80
Soulis, Ntoulas [43]	8 16	54.2	Pumice (65%), attapulgite clay (15%), zeolite (5%), and grape marc (15%)	50.6 54.8

Another important variable is the current moisture content of the substrate prior to a rain event [9,67]. Although some papers have suggested an uncertain correlation between the current moisture content of the substrate and rainwater retention [3,43,63], it strongly affects the substrate's retention capacity [3,5,39,44,45,65,68,69]. Dry substrate conditions before rainfall events will result in higher retention compared with initially wet conditions [63,67,68,71], as the runoff does not occur until the substrate is at field capacity [64,70]. Figure 6 demonstrates the different factors that affect the moisture content of the green roof substrate.

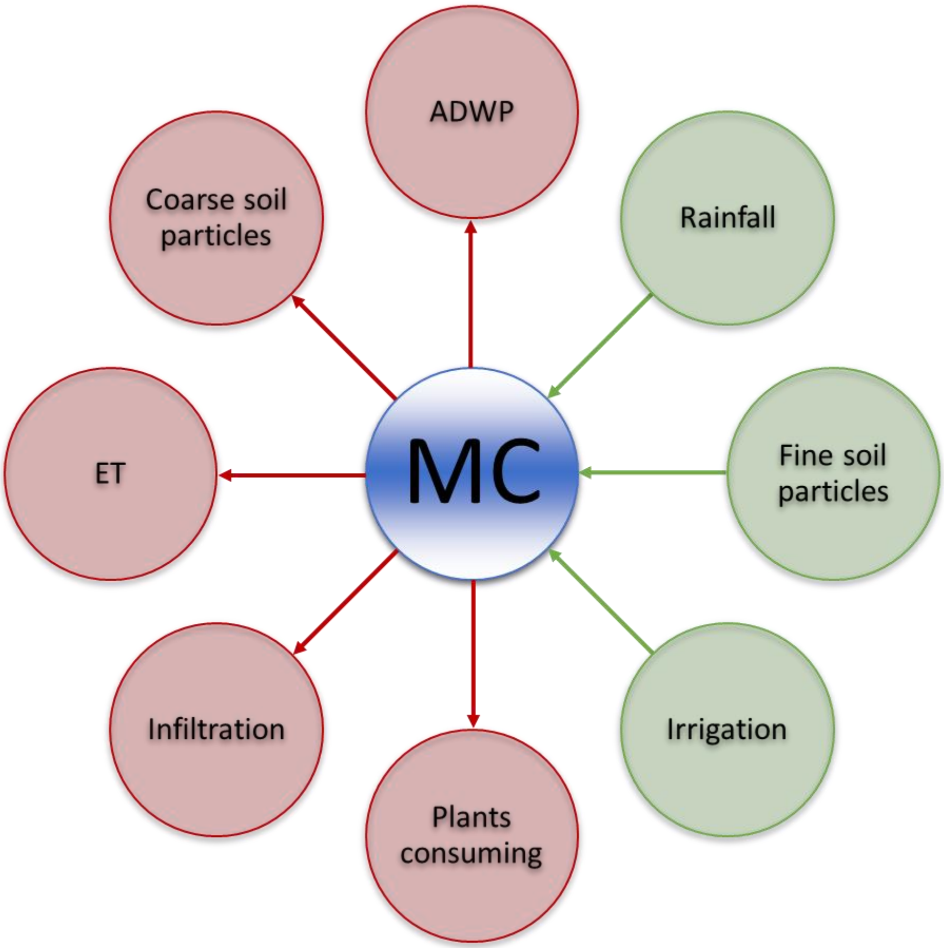


Figure 6. Effects of different factors on the substrate moisture content (MC) (red is negative, and green is positive). ADWP = anticipated dry weather period, and ET = evapotranspiration.

5.3.3. Vegetation

Vegetation is an important factor that substantially influences the moisture content of the substrate and the runoff rate of a green roof [28,78,79]. A reduction occurs through different processes, such as interception, transpiration, root uptake, retention, and water storage in plant tissue [3,71]. The water consumption of a plant determines its transpiration capacity, maturity, and root biomass and influences its water-storing capacity [21,69,71,80]. Increasing plant coverage on a green roof improves its ability to retain water [9], but species richness does not significantly affect the retention capacity unless different plants with higher water consumption rates are included [73,80]. Table 5 provides two examples of the effects of vegetation species on green roof runoff rates.

Vegetation exhibits seasonal fluctuations in water consumption due to various factors, especially during growing seasons when ET increases significantly [20,50]. The effect of vegetation on the total hydrological performance of a green roof varies among studies. While some studies show significant effects of vegetation on moisture reduction [81], others report its influence only in specific seasons [72]. However, selecting vegetation for green roofs is crucial and should be based on plant characteristics and the local climate [82]. For example, plant height and stomata are positively correlated with green-roof water retention capacity, and the selection of suitable plants can conserve or promote the consumption of water more efficiently [83,84].

Table 5. Selected studies on different plants and their effects on the rainwater retention of green roofs. RWR = rainwater retention.

Reference	Substrate Depth (cm)	Plants	RWR Rate (%)
Soulis, Ntoulas [43]	8	*O. onites*	63.6
	8	*S. sediforme*	50.8
	8	*F. arundinacea*	54.9
	8	-	50.6
	16	*O. onites*	81.1
	16	*S. sediforme*	60.3
	16	*F. arundinacea*	68.8
	16	-	54.8
Brandao, Cameira [42]	15	Mix of shrubs (*Rosmarinus officinalis*, *Lavandula stoechas subspecies Luisieri*), grass (*Brachypodium phoenicoides*), and moss (*Pleurochaete squarrosa*)	82
		Grass (*Brachypodium phoenicoides*)	73.2
		Shrub (*Rosmarinus officinalis*)	71.1
		-	64.2

5.3.4. Drainage Layer

The drainage layer, also known as the drainage system, is an essential component of a green roof [40]. This layer can be made of different materials, but it is usually composed of granular-based materials, such as aggregate and geo-composites [40,85]. Different drainage layer types and the used materials alter the runoff performance of green roofs (Table 6). The drainage layer is crucial for proper plant growth and controlling water-related issues and can act as a water storage system to balance water surplus and deficit [40]. The layer can have an additional water retention layer made of such materials as mineral wool, polymeric fibres, or rubber sheets, which also store water and release it slowly [19,86]. The drainage and water retention layers can serve as an active water retention layer, thus acting as a potential water source for the green roof [40,87,88]. This setup is crucial for water sustainability practices on green roofs [89,90], as it decreases the need for irrigation or replaces it completely [91]. Several studies have also introduced new materials and approaches to improve the efficiency of the drainage layer [21,77].

Table 6. Two examples of the influence of the drainage layer's properties on the green roof's runoff rate. RWR = rainwater runoff.

Article	Drainage Layer	Substrate Depth (cm)	RWR Rate (%)
Burszta-Adamiak [52]	Plastic profiled drainage elements type FKD 12 (height: 1.2 cm)	-	82.5
	Gravel with 2–5 cm granulation	-	85.7
Baryla, Karczmarczyk [77]	Polypropylene mat (Terrafond Garden 20 L type with a thickness of 2 cm) and geotextile fabric on top of the drainage layer	17	80
	Washed gravel	8	62.7
	Expanded clay aggregate	8	62.7

5.3.5. Other Influencing Factors

Several other factors can also influence rainwater retention, such as the slope of the green roof, its age, and the irrigation system used. Although a few studies found no association between a green roof's slope and the volume of retained water [4,56], others observed a meaningful correlation between them [10,66,87,92]. Table 7 presents three examples of studies that investigated the effects of different slopes on the runoff performance of green roofs.

Table 7. Selected studies on the effects of different slopes on green roof runoff rates. RWR = rainwater retention.

Article	Climate	Study Location	Green Roof Area	Substrate Depth (cm)	Slope	RWR Rate (%)
Getter and Rowe [10]	Temperate	USA	5.9536	6	2% 7% 15% 25%	85.2 82.2 78 75.3
Villarreal and Bengtsson [66]	Oceanic	Sweden	1.544	4	2° 8° 14°	62 43 39
Chow and Abu Bakar [93]	Tropical	Malaysia	2	13	0° 2° 5° 7°	56.9 56.4 55.9 52.3

Many researchers have investigated the effect of roof age on the hydrological performance of a green roof and found that the maturity of a green roof can be considered an important factor [71,94]. Berndtsson [9] stated that over time, the root's development and loss of soil particles, such as the washout of some dissolvable materials and various organic content, can change the growing medium's porosity, which will influence its hydrological performance. For instance, Getter and Rowe [10] monitored soil properties on a vegetated roof for five years and tracked the organic matter content and other physical properties. They found that the pore space and organic matter content doubled within this period from 41% to 82% and 2% to 4%, respectively, increasing the water-holding capacity from 17% to 67% [10]. Lastly, although irrigation is needed to help vegetation survive when the substrate is dried out and to improve the thermal performance of a green roof [2,94,95], the use of irrigation prior to anticipated rainfall increases the soil's moisture, thus reducing retention and increasing runoff during the next rainfall event [96,97].

5.3.6. Summary

The above subsections provided various influencing factors for the hydrological performance of green roofs. To increase clarity, Figure 7 summarises the hydrological performance of green roofs and the influencing factors.

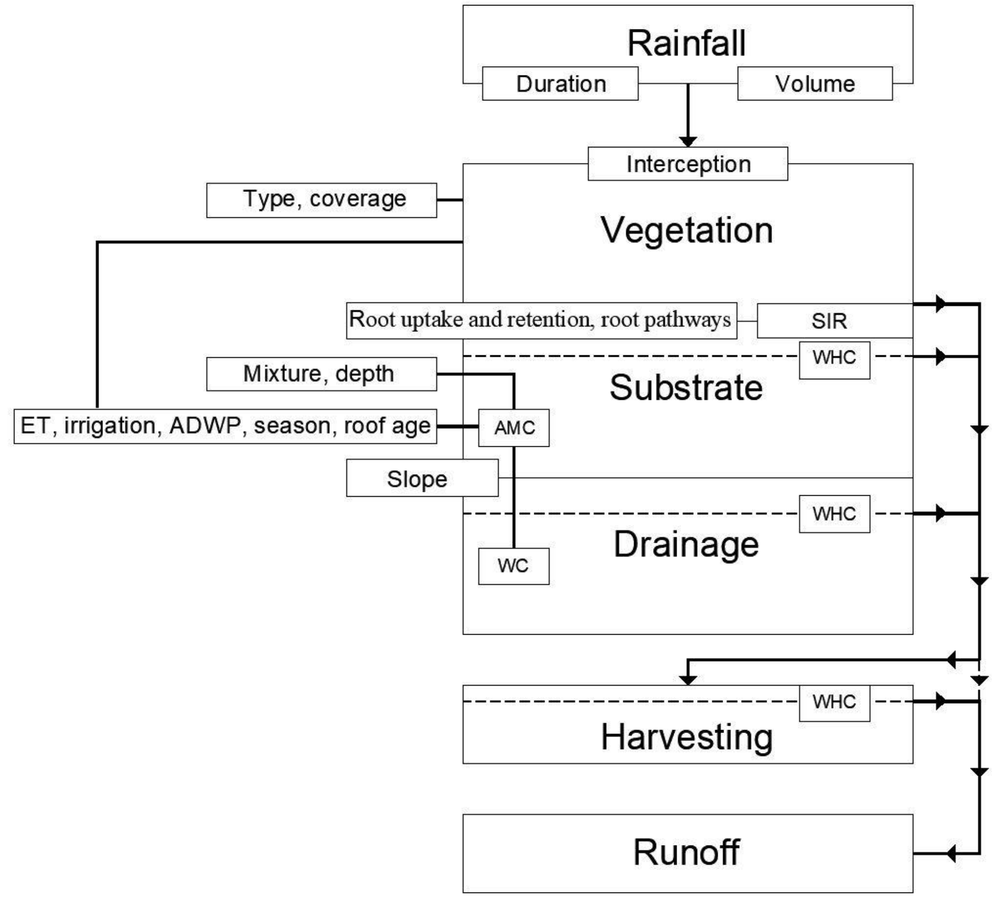


Figure 7. Hydrological performance of green roofs and the influencing factors. ET = evapotranspiration, ADWP = anticipated dry weather period, AMC = anticipated moisture content, WHC = water holding capacity, WC = water content, and SIR = substrate's infiltration rate.

6. The Impact of Green Roofs on Runoff Water Quality

6.1. Green Roofs as a Sink or a Source of Pollutants

On the one hand, green roofs can participate in improving runoff quality [98,99]. They can significantly remove pollution from passing water, such as suspended solids, toxic metals, petroleum hydrocarbons, and turbidity [32,33]. Depending on substrate composition, they can also increase the pH by up to 2.7 units [6,8,9,36], which mitigates the negative effects of acid rain [6,9,100]. For instance, Berndtsson and Emilsson [92] stated that green roofs behave as sinks for nitrate-nitrogen, with decreased ammonium nitrogen and total nitrogen percentage compared with the percentage in rainwater [92]. Similarly, van Seters and Rocha [101] reported that the pH and total of suspended solids, metals, nutrients, bacteria, and polycyclic aromatic hydrocarbons were lower in concentrations from a green roof compared with a conventional roof. In addition, Vijayaraghavan [102] mentioned that the substrate of a green roof performs as an ion exchange filter. It can lower the runoff's ion concentration [102].

On the other hand, some of the reviewed research indicated various pollutants and metal elements, nutrients, pesticides, and herbicides detected in green roof runoff [27,30]. For example, Vijayaraghavan and Joshi [100] reported substantial amounts of Na, K, Ca, Mg, NO_3, and PO_4 and traces of Fe, Cu, and Al in runoff from green roofs. Seidl and Gromaire [45] stated that green roofs produce higher phosphate, carbon, and organic nitrogen concentrations compared with traditional roofs. Ahmed and Huygens [103] found faecal indicator bacteria, potentially pathogenic bacteria, and protozoa in the runoff. Table 8 summarises the selected investigations of the quality of green roof runoff. Some of these studies concluded that green roofs are not suitable for harvesting rainwater compared with other roofs [104]. However, the concentrations of these pollutants are lower than those typically found in urban runoff [92], and the levels of observed nutrients and organic matter remain within the average concentration for wet-weather runoff in an urbanised watershed [45].

It can be concluded that green roofs may positively or negatively impact water quality, depending on a few factors. The following section summarises these factors.

6.2. Controlling Factors

Generally, green roofs store pollutants in the substrate, released when runoff or draining occurs [5]. Pollutants in the runoff greatly depend on runoff volume [9]. While Section 5 thoroughly investigated runoff volume, the following subsections focus on other controlling factors.

Table 8. Examples of studies on the impact of green roofs on runoff quality. Y = source, S = sink, I = increase, D = decrease, M = maintain, RW = rainwater, SRW = simulated rainwater, MSTW = metal-spiked tap water, and USTW = unspiked tap water.

Reference	**Green Roof Type**	**Substrate**	**Plants**		**Metal**													**Nutrient**								**pH**
					Zn	**Pb**	**Cd**	**Fe**	**Cr**	**Cu**	**Ca**	**As**	**Al**	**Mg**	**Ni**	**K**	**Na**	**NO^{3-}-N**	**PO_4^{3-}-P**	**TP**	**NO^{3-}**	**NH^{4+}**	**NH_4-N**	**DOC**	**DON DON**	
Chen, Kang [105]	10 cm extensive	cultivated (C), light (L), Cultivated +recycled glass (R)	*Sedum nussbaumerianum* (Sn)	RW	-	-	-	-	-	-	-	-	-	-	-	-	-	Y	Y	Y	-	-	S	-	-	I
	10 cm extensive		*Nephrolepis exaltata* (L.) *Schott* (Ne)		-	-	-	-	-	-	-	-	-	-	-	-	-	Y	Y	Y	-	-	S	-	-	I
	10 cm extensive		*Serissa foetida* (L.f.) *Poir.* (Sf)		-	-	-	-	-	-	-	-	-	-	-	-	-	Y	Y	Y	-	-	S	-	-	I
Buffam, Mitchell [106]	10 cm extensive	Tremco's standard aggregate-based	Mixed species.	RW	Y	-	-	Y	-	-	Y	-	Y	Y	-	Y	Y	-	Y	-	M	S	-	Y	Y	I
Schwager, Schaal [107]	Substrate	Pine Bark and Peat	-	SRW	Y	M	Y	-	Y	Y	-	Y	-	-	Y	-	-	-	-	-	-	-	-	-	-	-
		Coco Coir & Zeolite			Y	M	Y	-	Y	Y	-	Y	-	-	Y	-	-	-	-	-	-	-	-	-	-	-
		Compost and Slag and Clay			Y	Y	-	-	Y	Y	-	Y	-	-	Y	-	-	-	-	-	-	-	-	-	-	-
		Expanded Clay 1			Y	-	-	-	Y	Y	-	Y	-	-	Y	-	-	-	-	-	-	-	-	-	-	-
Vijayaraghavan and Joshi [108]	pilot-scale green roof	local garden soil	-	MSTW	S	S	S	S	S	S	Y	-	S	Y	S	Y	Y	-	-	-	-	-	-	-	-	I
		optimised green roof substrate	-		S	S	S	Y	S	S	S	-	Y	S	S	Y	Y	-	-	-	-	-	-	-	-	I
		local garden soil	*P. grandiflora*		S	S	S	S	S	S	Y	-	S	Y	S	Y	Y	-	-	-	-	-	-	-	-	I
		optimised green roof substrate	*P. grandiflora*		S	S	S	S	S	S	S	-	S	S	S	Y	Y	-	-	-	-	-	-	-	-	I
		local garden soil	-	USTW	S	-	-	-	-	Y	Y	-	-	Y	Y	Y	Y	-	-	-	-	-	-	-	-	D
		optimised green roof substrate	-		Y	-	-	Y	-	Y	S	-	Y	S	Y	Y	Y	-	-	-	-	-	-	-	-	D
		local garden soil	*P. grandiflora*		S	-	-	-	-	-	Y	-	Y	Y	-	Y	Y	-	-	-	-	-	-	-	-	D
		optimised green roof substrate	*P. grandiflora*		S	-	-	Y	-	S	S	-	Y	S	Y	Y	Y	-	-	-	-	-	-	-		D

6.2.1. Substrate Properties

As illustrated in Section 5, water can be contaminated or purified as it moves through the green roof substrate, which may differ based on the pollutant of interest [74]. Green roof substrates may include some metals (e.g., Zn, Pb, and Fe), nitrogen, organic matter, and other chemical components in different concentrations, depending on the composition of the materials and ameliorants [109,110]. Some of these components may dissolve or be discharged with the runoff, causing reduced water quality and increased turbidity [102]. The concentrations of the pollutants found in the runoff depend on the proportion of these pollutants in the substrate [9,28,102]. In addition, the substrate's material and composition can affect the leaching amounts of the contaminants. For example, an increase in silting components increases the leaching of nitrate-N, DOC, DON, and orthophosphate-P [36]. Using sand media instead of clay can boost ammonia loss [111]. Furthermore, the magnitude of contaminants in the runoff is affected by soil microbes and their secretions and metabolites [27,92,102,112]. The substrate's depth can positively or negatively affect runoff quality [110], depending on the pollutant type and if the substrate is a source of this contamination or a sink [45,74,111]. Therefore, careful attention to substrate design and composition and ongoing monitoring and maintenance can help improve water quality management in green roofs.

6.2.2. Vegetation

Generally, the reviewed papers agreed that vegetation plays a functional role in reducing the magnitude of pollutants in runoff [41,78,79], specifically when vegetated roofs are compared with non-vegetated roofs [36,57,113]. Vegetation participates in removing pollutants, as it acts as a particle trap for dust, airborne particulates, and biofilters [102,114]. In addition, vegetation supports microbial activity in the substrate layer, which can help break down pollutants and improve runoff quality [115]. A few studies showed that the pollution caused by green roofs is associated with the release of nutrients, which increases if the uptake of the plants is limited [12,27,112]. Plants need nutrients for different physiobiological processes, and these macronutrients can be accumulated through the root system [116], although the retention ability varies between species [117]. Therefore, plant selection should match the substrate composition and the added fertilisers [9,118], considering that plant diversity can reduce some pollutants in the runoff in contrast to monocultures [119]. Plants may also be a source of pollutants, as decaying plant litter, dead roots, and the decomposition of regenerated roots can change the balance of the substrate layer to increase pollutant sources, mainly microbes [27,112].

6.2.3. Other Factors

Green roofs can suffer from pollution due to the accumulation of airborne pollutants from coal burning, vehicle exhaust, and waste combustion [27]. These pollutants can accumulate on the surfaces of plants and substrates on green roofs through deposition during rain events [24] or via gravity. Dissolved chemicals from fertilisers and pesticides used for vegetation growth can also contribute to pollution [12]. The runoff water quality from green roofs can vary according to the age of the roof, with newly constructed green roofs having higher concentrations of nutrients that are reduced over time by rainfall flushing, plant uptake, and biological activities [9,32,78,102]. Heavy metals tend to increase in concentration within green roof layers during dry periods, and ageing green roofs can release them [92]. Seasonal variations also affect green roof runoff quality, with significant differences observed in nutrient concentrations between summer and winter. Therefore, it is important to carefully select plants and fertilisers and consider environmental conditions when designing green roof systems to maintain water quality [27,120].

7. Techniques to Control Runoff and Water Consumption on Green Roofs

The techniques used to control runoff and water consumption on green roofs are closely related, as they aim to increase water management sustainability and mitigate the environmental impacts of urban development. Therefore, it is important to consider the interdependence of these two factors when designing and maintaining green roofs.

7.1. Evaluating and Controlling Potential Evapotranspiration

ET is the process of water transpiring from the soil through direct evaporation and plant transpiration [121]. ET rates are affected by various factors, such as climate conditions (e.g., temperature, wind speed, and solar radiation), vegetation, and substrate and moisture content [4,122]. ET reduces the available moisture content of the substrate, leading to increased green-roof retention and detention capacity during rainfall events [4,50,122]. It is considered an effective mechanism in reducing runoff [122], and Ebrahimian and Wadzuk [123] found that the annual green-roof retention capacity due to ET ranged between 11% and 77% of the total rainfall volume. Various substrate characteristics can affect water retention capacity and ET rates [122]. The vegetation layer is also a crucial factor affecting ET, with its availability increasing the ET rate [87]. Different plant species have varying rates of ET; some species, such as *Origanum onites*, have a high ET capacity, while others, such as turfgrass, have a moderate ET capacity [43,122]. Therefore, selecting the appropriate plant species is essential for improving green-roof hydrological performance under different climatic conditions and irrigation methods [43]. It is also important to consider both ET and infiltration concurrently in the design of green roofs to improve their hydrological performance [123]. Finally, adding artificial shading or trees on green roofs, specifically in hot climates, may reduce the exposure of low canopy vegetation to the sun's rays, which can help reduce the green roof's surface temperature and enhance water balance efficiency [72,83,124,125]. Figure 8 shows the influence of different factors on ET that designers must consider in the green roof design process.

7.2. Adapting Green Roof Layers and Considering Non-Traditional Green Roof Types

As mentioned in Section 5.3, green roof layers play an essential role in controlling hydrological performance. Therefore, adapting these layers to the local rainfall intensity and depth will increase the green roof's hydrological performance. This includes selecting the appropriate growing medium composition with the appropriate depth and moisture-holding capacity [20,40,58,71–73], vegetation coverage that matches the anticipated ET and water availability [21,69,71,80], and the appropriate drainage layer materials that retain a sufficient amount of water to mitigate the need for irrigation [40,87,88], as well as reducing the slope of the green roof to reduce runoff speed [10,66,87,92]. However, when traditional green roof settings are insufficient to promote sustainable water management practices, considering non-traditional green roof types, such as blue-green roofs, purple roofs, sponge roofs, and constructed wetlands, may be highly beneficial for more sustainable water management. Non-traditional green roof types have additional layers or modifications to adapt to specific environmental challenges. For instance, a blue-green roof combines the benefits of a traditional green roof with a water storage layer that allows for the controlled release, storage, and filtration of rainwater, and it is effective in areas with heavy rainfall or a high risk of flooding [87]. A purple roof is similar to a traditional green roof but incorporates a drainage layer with low transmissivity and a void layer that can be tailored to different depths to permit water storage for gradual release, and it is also suitable for wet climates and drought-prone regions [126,127]. A sponge roof is a lightweight version of a green roof due to incorporating a lightweight structure, such as mineral wool, in its design, which can hold water and discharge it slowly [126]. Lastly, a constructed wetland is designed to mimic the natural processes of a wetland and its capability to retain and purify water [128,129].

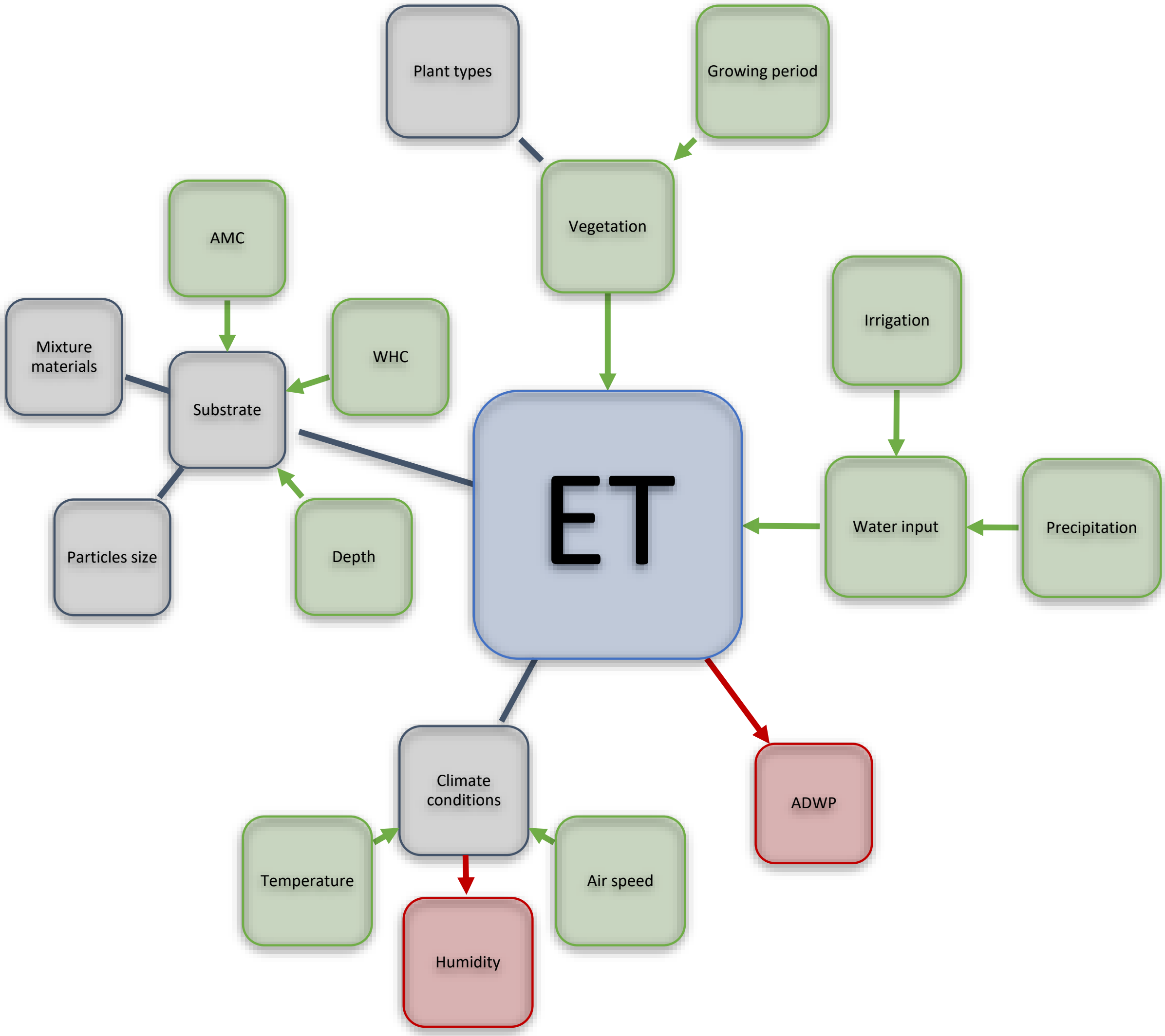


Figure 8. Influence of different factors on evapotranspiration (ET), ADWP = anticipated dry weather period, AMC = anticipated moisture content, and WHC = water-holding capacity. Green = positive, red = negative, and grey = two-way effect.

7.3. Controlling the Irrigation Regime

Irrigation is necessary to maintain the vitality of a green roof's vegetation during the anticipated dry weather period and plant establishment and to improve the green roof's thermal performance [95,130]. Installing an irrigation system during the green roof design phase is less expensive than replanting dead plants [131]. However, a permanent irrigation system may not be necessary after plant establishment if the green roof is appropriately designed and considers all the factors mentioned in the previous sections, such as retaining sufficient rainwater, growing medium type and depth, and plant selection [88,132]. When the potential ET exceeds the monthly precipitation, an imbalance in the green roof's hydrological performance occurs in climates with extended dry weather periods, particularly in hot weather. Therefore, installing an irrigation system is essential.

ET and weather conditions are critical factors when designing and controlling an irrigation regime [122,133]. Predicting the ET of the current hour and calculating the required amount of water for irrigation is essential for designing a precise irrigation system to water the plants directly at their roots according to their needs [76,121]. In addition, evaluating the current substrate moisture content and its suitability to support the plants' survival while waiting for the predicted next rainfall will maximise the green roof's retention performance [96,97]. One example of such a system is the artificial irrigation system developed by Bandara and Balasooriya [121], which measures the surrounding climate status, calculates the average values and predicts the anticipated climatic status to determine the required amount of water for irrigation. Although irrigation systems are necessary to improve green roof performance from various aspects, the knowledge of irrigation practices and specifications on green roofs is still limited [22].

7.4. Harvesting the Runoff

After all the above techniques are considered, runoff may still occur and harvesting the runoff is the last technique that may be applied. The harvested runoff can be used for irrigation and non-potable purposes [28,134]. Studies have shown that harvested runoff may account for 34–92% of the total water consumption of an average household, depending on a typical family's demand [135]. Different methods can facilitate harvesting, including installing tanks, cisterns, or rain gardens [33,136].

8. Techniques to Control the Runoff Quality from Green Roofs

As discussed in Sections 4 and 6, water sources and green roof layers affect runoff quality. The best strategy to control the leaking of pollutants is to reduce runoff [8,9,58,92], which provides a better chance that plants or biosorbents will take up these pollutants [137]. However, if the green roof design does not allow for hosting all the provided water, using high-grade water sources and high-quality substrates may significantly help enhance runoff quality [45,74,111]. In addition, it is important to acknowledge the possibility of leaching pollutants and take steps to minimise their impact, ultimately enhancing the runoff quality. The following subsections outline several practical approaches to accomplish this goal.

8.1. Phytoremediation

Phytoremediation is an efficient, cost-effective, and eco-friendly solution that uses plants and their associated microbes to reduce the concentrations or toxic effects of pollutants in the environment [138,139]. Phytoremediation techniques, such as phytoextraction (Figure 9), phytofiltration, phytostabilisation, phytovolatilisation, phytodegradation, rhizodegradation, and phytodesalinsation [139,140], can be used to improve the quality of green roof runoff and the harvested water. For example, phytoextraction can remove heavy metals and metalloids [139,141] through hyperaccumulator plants [142,143]. Phytofiltration filters contaminants from water sources using *Spathiphyllum* spp., for instance [144]. Phytostabilisation immobilises contaminants in the substrate by using plants such as *Sempervivum* spp. [145]. Phytovolatilisation takes contaminants and releases them into the atmosphere in a less harmful form using such plants as *Lavandula* spp. [146]. Rhizodegradation uses plants (e.g., *Trifolium* spp.) and their associated microbes to degrade contaminants in the soil [147]. Phytodesalination removes salt from saline soils or water using plants (e.g., *ice plants*) [148].

8.2. Biosorption

Biosorption is a bioremediation technique that uses inactive or dead biological materials, such as algae, fungi, bacteria, and agricultural and industrial wastes, to absorb organic and inorganic pollutants to improve runoff quality [139,149]. Many researchers reported that adding mycorrhizal fungi to the substrate can effectively decompose, absorb, and retain nutrients and metals [26,27,120]. Seaweed (which is classified as brown algae), red algae, and green algae demonstrate significant performance in treating heavy metals [57,139]. Adding biochar to the substrate can increase the nutrient retention capacity and remarkably decrease the leaching of total nitrogen, total phosphorus, nitrate, phosphate, and organic carbon [27,117]. Expanded shale can increase the capacity for retaining P, NH4-N, and metals [150]. Adding crab shells is also an excellent biosorbent treatment for various metals and other pollutants [139]. Adding seashell media can help remove sulphide odours (rotten eggs and rotten vegetables) and some faecal odours up to 99% [151].

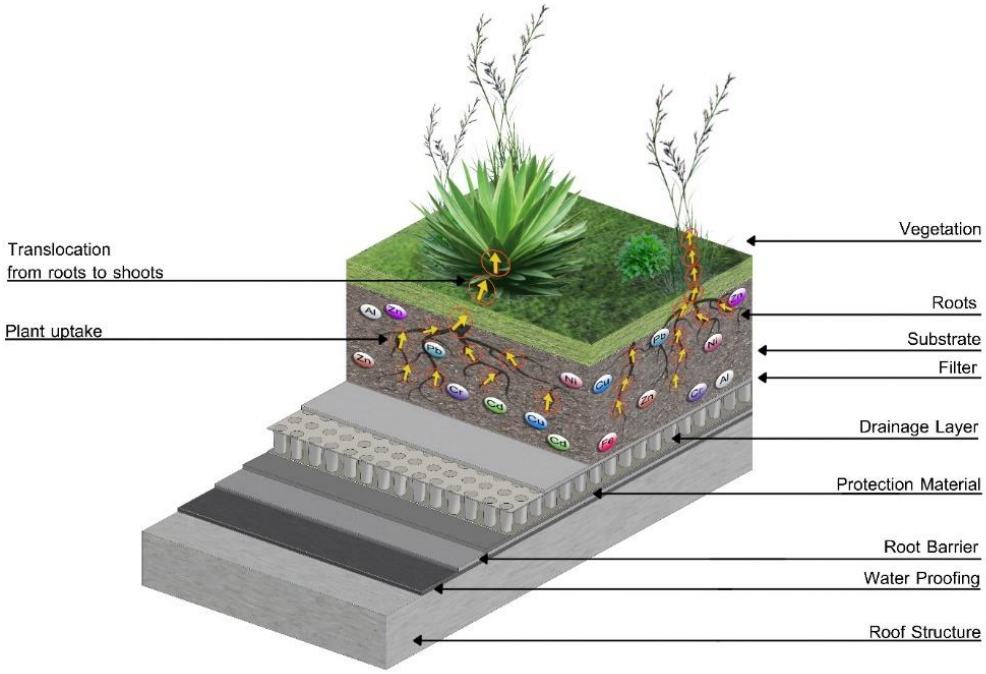


Figure 9. Phytoextraction of metals from the contaminated substrate in a green roof (adapted from [139]).

8.3. Controlling Fertilisers and Pesticides

Fertilisers and pesticides are often used to enhance vegetation performance and health. However, they contaminate the runoff and harvested water. The negative impacts of fertiliser and pesticide use can be reduced by avoiding application during the wet season and just before rainfall occurs [111] and by using a controlled-release fertiliser [111,113], in addition to improving the knowledge of the plants' nutrient requirements to develop a proper fertilisation protocol suited to the various growth stages of the plants or to balance nutrient losses. For example, plants only require phosphorus during the establishment stage, and most plants require nitrogen during their rapid growth periods [111]. Chen et al. (2011) applied precise irrigation and synchronised nitrogen supplies to successfully decrease nutrient loss to nearly zero [152], compared with the 127-kg N/ha loss in typical practices [9,111].

9. Discussion

This review aimed to explore the influencing factors and innovative solutions that increase the sustainability of water management on green roofs. The study incorporated an investigation of the state of the art and focused on the hydrological balance, water input and output, key influencing factors, and techniques that enhance hydrological performance. Most of the reviewed studies involved small experimental extensive green roof platforms, and these types of experiments may over- or underestimate the performance of actual green roofs [4,45]. However, such research can help provide insights into various green roof settings, such as different slopes, vegetation, and substrate depth levels. The results of these studies can help understand and evaluate the performance of green roofs, but they should be used as guidance and not as facts to be applied directly to policies without further investigation.

Green roofs can manage rainwater on buildings and support stormwater management in cities if designed appropriately, but their performance is limited in extreme events and conditions [21,39,64,65]. Enhancing rainwater retention on green roofs may help reduce the negative impact of green roofs on water resources, as rainwater is considered a renewable water source. This can be achieved by estimating the rainfall amount and annual distribution and controlling the water storing capacity and consumption of green roofs by amending green-roof settings or integrating the various technologies discussed in

Section 7. Seeking non-potable sources, such as greywater, or harvesting enough rainwater to be used for irrigation during dry weather periods is highly advantageous for improving the sustainability of green roofs.

In addition, the water balance of a green roof depends on its configuration, design, and hydrological loading ratio. The latter has a significant influence on ET, which is the greatest water consumption factor for green roofs [123]. Many factors lead to increasing or decreasing ET, as explained in Section 7.1, according to what is needed to serve the green roof's performance. Therefore, it is essential to set the appropriate objective of establishing a green roof with the correct configuration of these controlling factors and to evaluate the overall positives and negatives of the green roof. For instance, this assessment is critical when considering a green roof for the thermal comfort aspect, as this performance depends greatly on water consumption in the ET mechanism.

Furthermore, although only one research paper among the reviewed articles emphasised developing water management plans for green roofs [153], a comprehensive water management plan is essential for successfully implementing sustainable green roof technology. However, it is difficult to derive a good water management plan from the published articles due to the enormous differences between the climate conditions in the various observed zones and the different objectives for implementing green roofs. In addition, no information about the acceptable thresholds for green roofs' water consumption or runoff in city regulations was found. Therefore, it is recommended that designers seek modelling tools (e.g., EcoRoof in EnergyPlus) to assess the potential ET, required irrigation, and anticipated runoff by considering substrate infiltration (which couples the soil matrix and hydrologic aspects with the usage of rainfall records) and climate data for their design strategies and water management plans for green roofs. In addition, cities should request a water management plan as an approval requirement for green roof implementation. Such a plan should be assessed based on the availability of water resources within the city and the potential impact of green roofs on these resources. Lastly, city councils should be motivated to collaborate with researchers to highlight the needed thresholds for green roofs' water consumption and runoff to develop the best practices regarding green roofs in cities.

Green roofs can function either as a sink or a source of pollutants, depending on their specific locations, settings, and water sources. Therefore, green roof layers should be modified to improve water quality or, at the very least, prevent a reduction in water quality based on the factors discussed in this review and the solutions provided in Section 8. It is important to note that identifying the sources and concentrations of pollutants and using appropriate techniques are crucial for effectively enhancing water quality. Based on that, the manufacturers of various green roof construction materials, particularly substrates, should be urged to provide evaluations of their products' impacts on runoff quality. Such evaluations will aid in improving the overall assessment of green roof performance in terms of water quality. City councils and building rating systems should incorporate a request for an assessment of the impact on stormwater quality by the selected green roof settings. This will motivate designers to enhance their green roofs' sustainability, improve rating systems, and facilitate city councils' initiatives and incentives regarding green roofs.

9.1. Practical Implications and Proposed Framework

This review provided important information regarding the various influencing factors and innovative solutions to help decision-makers undertake a sustainable water management plan for green roofs. Therefore, based on the above, this section aims to synthesise the existing knowledge to guide designers and policymakers to enhance their strategies for managing water on green roofs. As a result, a sustainable water management framework has been developed. The framework consists of seven stages followed by feasibility assessment and decision-making, as presented in the following sub-sections.

9.1.1. Proposed Sustainable Water Management Framework

1. Site assessment and planning:
    a. Prioritise water management objectives: rank and prioritise water management objectives based on their significance and feasibility for the project.
    b. Integrate water management into site planning: ensure water management is integrated with the overall site planning process, considering factors such as building design, landscaping, and infrastructure.
    c. Assess local regulations and permits: ensure compliance with local regulations and obtain necessary permits and guidelines for water sources and management.
    d. Comprehensive site assessment: conduct a thorough site assessment, including climate conditions, rainfall patterns, access to sunlight, roof slope, neighbouring buildings, pollutants, vegetation, and drainage systems.
2. Green roof design and configurations:
    a. Select appropriate green roof type: determine the most suitable green roof type based on site-specific factors and water management objectives.
    b. Optimise water management design: design the green roof to optimise water management, considering factors such as slope, drainage systems, substrate composition, and vegetation selection.
    c. Emphasise water conservation strategies: incorporate water conservation strategies, such as using drought-tolerant plant species, mulching, retention layers, and water-efficient fixtures.
    d. Efficient drainage system: design an efficient and well-structured drainage system to manage excess water and prevent waterlogging.
3. Irrigation design and management:
    a. Estimate water demand: estimate the water demand for the site based on vegetation requirements, evapotranspiration rates, and irrigation needs.
    b. Develop a smart irrigation plan: develop an irrigation plan that considers water needs, availability, and conservation goals. Implement smart irrigation controllers adjusting schedules based on weather conditions, soil moisture, and plant requirements.
    c. Efficient irrigation systems: implement efficient irrigation systems, such as drip irrigation or sub-irrigation, and incorporate moisture sensors to optimise water use and prevent overwatering.
    d. Explore alternative water sources: encourage using greywater or recycled water for irrigation, if feasible and permitted.
4. Excess and rainwater harvesting:
    a. Assess the feasibility of rainwater harvesting: evaluate feasibility based on rainfall patterns, roof area, and water storage capacity.
    b. Design a rainwater collection system: design and implement a rainwater collection system, including gutters, downspouts, and storage tanks, considering the water requirements of the green roof.
5. Runoff control and stormwater management:
    a. Retain and gradually release water: implement methods to retain and gradually release stored water from the drainage layer, reducing the burden on conventional drainage systems.
    b. Integrate with green infrastructure: incorporate green roofs with other green infrastructure elements, such as bioswales or rain gardens, to enhance stormwater management.
    c. Ensure a functional drainage system: design and maintain a well-functioning drainage system to direct excess water away from the building and prevent damage.
6. Water quality management:

   a. Enhance water quality on green roofs: implement measures such as appropriate vegetation, substrates, and filtration systems to enhance water quality on green roofs.
   b. Regular water quality monitoring: conduct regular monitoring and testing of water quality parameters to ensure compliance with local regulations and standards and implement required techniques to enhance the quality if needed.
7. Maintenance, monitoring, and improvement:
   a. Develop a comprehensive maintenance plan: develop a comprehensive maintenance plan, including regular inspections, cleaning of drainage systems, and vegetation management.
   b. Monitor performance and consumption: monitor water consumption, stormwater runoff, and overall system performance to identify opportunities for improvement and address any issues promptly.
   c. Periodic inspections and adjustments: conduct periodic inspections to identify and address potential issues and make necessary adjustments to optimise water efficiency and sustainability.
   d. Stay updated on advances: stay informed about advances in green roof technologies, water management strategies, and best practices through engagement with research institutions and industry experts.
   e. Stakeholder feedback and engagement: seek feedback from stakeholders, including building owners, occupants, and facility managers, to understand their needs, preferences, and concerns regarding water management. Involve stakeholders throughout the process to ensure their support and participation.

9.1.2. Feasibility Assessment

1. Cost-benefit analysis: conduct a detailed cost-benefit analysis to determine the economic feasibility of implementing the green roof water management system. Evaluate installation costs, maintenance expenses, and potential savings in water bills or stormwater management infrastructure.
2. Environmental impact assessment: assess the potential environmental benefits of the green roof water management system, such as reducing stormwater runoff and improving water quality. Consider the life cycle environmental impacts of materials and maintenance practices.
3. Technical feasibility: evaluate the technical feasibility of implementing the required systems, including green roof design, irrigation systems, rainwater collection and drainage infrastructure.
4. Risk assessment and mitigation: identify and evaluate potential risks associated with green roof water management, such as leakage, water damage, or increased maintenance requirements. Develop mitigation strategies to minimise risks and ensure long-term performance.
5. Social considerations: engage with stakeholders to understand their needs and concerns related to water management, specifically for the water sources used for irrigation.

9.1.3. Decision-Making

1. Informed decision-making: based on the assessments conducted, stakeholder input, and feasibility analysis, make an informed decision on the practicality of implementing the green roof water management system. Consider alternative approaches or modifications if necessary.
2. Scalability and adaptability: assess the scalability of the system to other projects and consider adaptability to different contexts. Ensure that the framework can be replicated and adjusted based on varying site conditions, regulations, and resources.
3. Continual improvement: continuously evaluate the performance of the green roof system in terms of water management goals and objectives. Monitor water usage,

rainfall, runoff and system efficiency to identify areas for improvement and implement necessary adjustments.
4. Knowledge updates: stay updated on the latest advances in green roof technologies, water management strategies, and best practices. Engage with research institutions, industry experts, and relevant professional networks to stay informed and incorporate new knowledge into the water management framework.

9.2. Limitation and Future Studies

The limitation of this study is subject to the existing literature in that the majority of the reviewed studies were conducted on small experimental extensive green roof platforms, which may over- or underestimate the performance of an actual green roof. Future research should prioritise large-scale monitoring studies to assess the economic and social feasibility of green roofs for water management. Additionally, it is crucial to investigate the impact of green roofs on the broader urban water cycle and how they interact with local water resource management policies. Further research should also explore the integration of green roofs with other green infrastructure components, such as bioswales and rain gardens, to develop a comprehensive approach to stormwater management in urban areas. Currently, irrigation strategies and systems remain inadequately studied; thus, future research should address this gap by exploring related systems and strategies. It is essential to note that the research approach that views green roofs as a homogenous layer regardless of their settings is overused. Consequently, a combination of various green roof types and their different integration methods should be investigated to improve their sustainability and introduce the best green roof settings and better practices. In addition, while plants on green roofs can absorb pollutants, they can also shed plant materials, such as leaves, dead roots, and the decomposition of regenerated roots, which can change the balance of the substrate layer and increase pollutant sources. Further research is required to assess the impact of the most commonly used plant species on green roofs on water quality throughout their life cycles. Expanding the scope of research sites to include large-scale green roof installations across diverse locations, climates, and building types is also recommended. This will provide a broader range of conditions and enhance the generalisability of findings. Additionally, conducting long-term monitoring studies of green roofs will contribute valuable insights into their performance, effectiveness, and long-term economic and social feasibility. Lastly, an analysis of the broader urban water cycle is necessary to evaluate the overall impact of green roofs, including factors such as stormwater runoff, groundwater recharge, and their compatibility with existing water resource management policies. Integration with other green infrastructure elements, such as bioswales, rain gardens, and permeable pavements, should be explored to develop a comprehensive and resilient approach to urban stormwater management.

10. Conclusions

This review explored the factors influencing the sustainability of water management on green roofs and the innovative solutions that can be implemented to improve their hydrological performance. The review highlighted the need for the appropriate design, configuration, and management of green roofs to enhance their water retention capabilities, reduce their impact on water resources, and support city stormwater management. However, it is essential to note that the performance of green roofs may be over- or underestimated in small experimental platforms, and the results should be used as guidance rather than direct facts for policymaking. The review also emphasised the importance of developing comprehensive water management plans considering local climate conditions and the objectives for implementing green roofs. Modelling potential ET based on substrate infiltration and climate data can facilitate effective design strategies and water management plans for green roofs. In addition, it is essential to consider the sources and concentrations of pollutants in implementing green roofs, particularly in areas with poor air quality or varying irrigation water quality. Furthermore, manufacturers of green roof materials should provide evaluations of their products' impacts on runoff quality. This will influence the designs, selections, or modifications of the layers of green roofs and the implementation of appropriate techniques that improve water quality. Finally, policymakers should require water management plans to be submitted for approval and develop suitable frameworks for water management on green roofs for their cities based on the framework provided in this study.

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