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REVIEW ARTICLE

Sustainable green roofs: a comprehensive review of influential factors

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Abstract

Green roofs have gained much attention as a modern roofing surface due to their potential to deliver many environmental and social benefits. Studies have indicated that different GR designs deliver different ecosystem services, and there are important factors that affect GR performance. This article reviewed significant factors that influence GR performance and sustainability. Substrate and drainage layer material choice significantly affects stormwater retention potential, leachate quality, plant survival, and determines GR environmental footprints. Subsequently, type of plants, their form, and kinds used on GRs impact GR ecosystem function. Leaf area is the most studied trait due to its influence on the cooling potential and energy performance. In order to achieve a sustainable GR, it is essential to select the type of plants that have a high survival rate. Perennial herbs, particularly forbs and grass as dominant groups, are heat and drought tolerant, which make them suitable in GR experiment. Furthermore, selecting a suitable irrigation system is as important as two other factors for having a sustainable GR. Irrigation is essential for plant survival, and due to the current pressure on valuable water sources, it is important to select a sustainable irrigation system. This review presents three sustainable irrigation methods: (i) employing alternative water sources such as rainwater, greywater, and atmospheric water; (ii) smart irrigation and monitoring; and (iii) using adaptive materials and additives that improve GR water use. This review sheds new insights on the design of high-performance, sustainable GRs and provides guidance for the legislation of sustainable GR.

Keywords Green roof · Local materials · Plant species · Sustainable irrigation · Integrated design · Environmental footprint

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Introduction

Global disruptions such as COVID-19 (Yu et al. 2021) and climate change have brought attention to the importance and quality of our built and natural environments. How we construct and build cities must change if we want to move toward cities with more resilience, sustainability (Addanki and Venkataraman 2017; Bibri and Krogstie 2017; Teixeira et al. 2021), and greater access to nature (Sharifi 2021). Green infrastructure is an essential part of sustainable and healthy cities that include parks, green spaces, and low-impact development practices such as green roofs (GRs) (Suppakittpaisarn et al. 2017; Langemeyer et al. 2020; Liberalesso et al. 2020). Green infrastructure has a wide range of environmental benefits (Santamouris and Osmond 2020; Changsoon et al. 2021) and can increase the resilience and health of the urban systems toward several risk categories like mitigating stormwater runoff (Kim and Song 2019; Parker and Zingoni de Baro 2019).

GR guidelines and standards have been developed in Europe and North America to enlighten about state-of-the-art performance expectations for GRs. For example, the "Guidelines for the Planning, Construction and Maintenance of Green Roofing," commonly referred to as the German FLL Guidelines for GRs (FLL 2018), are one the most widely used and detailed guidelines among others (Dvorak 2011). The German FLL guidelines for GRs specify desirable material choices, the weights of various reclaimed materials that can be used as drainage layers, weights of common forms of plants, nutrient and chemical ranges for substrates, and ranges of water flow through and retention rates among many other system elements (FLL 2018). The FLL guidelines for GRs include information about how GR can be made to be resilient and sustainable, such as how to minimize environmental pollution and add positive benefits for urban ecosystems and building owners and users.

Three types of GRs are recognized based upon their level of complexity: extensive, semi-intensive, and intensive GRs (Raji et al. 2015; FLL 2018). Extensive GRs are shallow light-weight systems (60 to 150 kg/m^2) that typically have a growing medium depth of 5 to 15 cm (FLL 2018). Plant diversity is generally limited due to the shallow substrate depths; however, these are the most frequent kind of application of GRs due to their low cost.

Semi-intensive GRs (also known as simple intensive) have intermediate characteristics of extensive and intensive GRs. This type has weight and thickness greater than extensive GRs and lower than intensive GRs. Semi-intensive GRs typically have substrate depths of 15–25 cm (FLL 2018). Semi-intensive GRs generally accommodate a wide variety of types of vegetation due to their substrate depth. Intensive GRs have deep substrates (> 25 cm) and a wide variety of vegetation that can include shrubs and trees (Droz et al. 2021b; Manso et al. 2021). Our review addresses application of extensive and semi-intensive GR, because of their intended widespread application and environmental benefits.

GRs have several layers of materials (Fig. 1), including the vegetation layer, substrate layer (growing media), water retention layer, filter layer, drainage layer, root barrier, and protection layer (Bozorg Chenani et al. 2015). Vegetation is planted into the substrate; therefore, the materials and nutrients of the substrate layer support plant growth and plants' physiological performance (Young et al. 2014).

The water retention layer captures stormwater and reduces rooftop runoff, and also provides water for plants (Simmons et al. 2008). The filter layer is above the drainage layer and prevents substrate fine particles from passing through the drainage layer. By removing excessive water through its porosity, the drainage layer is responsible for providing a balance between drainage and water retention and adequate root aeration. The protection layer and root barrier are placed at the lowest level of the layers, protecting the building structure from penetration of vegetation roots and small-sized particles into the structures (Bozorg Chenani et al. 2015).

Some cities require the use of GRs on some buildings due to the many ecosystem services that GRs provide. GRs can reduce air pollution (Banirazi Motlagh et al. 2021), reduce urban heat islands (Kolokotsa et al. 2013; Santamouris 2014; Imran et al. 2018; Yang et al. 2018; Asadi et al. 2020; Tiwari et al. 2021), sequester carbon (Shafique et al. 2020; Sultana et al. 2021; Seyedabadi et al. 2022), reduce rooftop stormwater runoff (Shafique et al. 2018; Jusić et al. 2019; Kolasa-Więcek and Suszanowicz 2021; Wang et al. 2022b; Wang et al. 2022a, b), cool down the ambient temperature (Zhang et al. 2020; Dandou et al. 2021; Jamei et al. 2021; Zheng et al. 2021), and mitigate urban heat islands (Aghamohammadi et al. 2021a, b; Aghamohammadi et al. 2021b) and air pollution (Hong et al. 2021; Wang et al. 2021a, b).

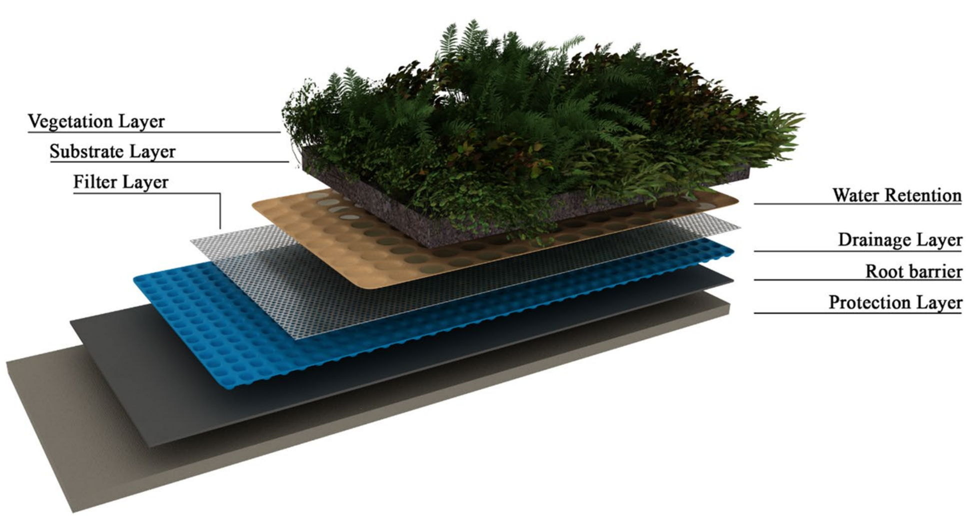

Fig. 1 *Layers common to multilayer GRs.* Source: author's design

The vegetation and substrates of GRs are also known to reduce energy demands (Aboelata 2021; Bevilacqua 2021; Movahed et al. 2021; Rafael et al. 2021; Alim et al. 2022). Because of the wide variety of ecosystems services provided by GRs, many cities have implemented legislation and development incentives (Carter and Fowler 2008; Chen 2013). For example, in Toronto, Canada, commercial, institutional, and residential buildings with more than 2000 m^2 roof area are required to include 20–60% of the roof area as GRs (Chow et al. 2018). In Tokyo, Japan, new buildings are required to include 20% roof vegetation coverage, while 15% GR coverage is required in Basel, Switzerland and 70% in Portland, USA (Townshend and Duggie 2007). In Chicago, the USA, up to 50% of the cost of implementation will be supported if the GR covers higher than 50% of the net roof area (Berardi et al. 2014). However, most of these policy actions only focus on GR coverage and speeding up the implementation of GRs around the cities, regardless of their performance and environmental impacts. In spite of the fact that GR performance, sustainability, and environmental impacts can be significantly altered by only changing some of the influential factors.

Sustainable aspects of GRs include their inert materials, live materials (vegetation), and the use of water. Inert materials include the GR substrate and drainage layers, both of which can be made from recycled, reused, and locally sourced materials ("Substrate and drainage materials" section).

The appropriate selection of vegetation is essential to the overall performance of GRs (Lundholm and Williams 2015). In this paper, we investigate plant traits and other factors related to plants that influence GR performance ("Plants and green roof performance" section).

The third aspect influencing sustainable GRs is water-use and irrigation. We investigate ways that irrigation influences GR sustainability and improves its performance. In some climates, irrigation is vital for GRs since the plants' survival relies on it, and also, GR cooling potential can be enhanced by a suitable irrigation approach (Van Mechelen et al. 2015). Sustainable GRs employ alternative water sources such as rainwater, greywater and innovative sources (atmospheric water). GRs can make use of smart irrigation and monitoring, and also adaptive materials and additives can be used to improve water use in GRs ("Sustainable irrigation" section).

Since GRs are becoming employed and legislated into municipal ordinances, it is important to understand how GRs can be made to be sustainable and resilient interventions. This study aims to reveal influential factors of high-performing GRs and GRs with minimal adverse environmental impacts. To address these important aspects of GRs, we employ a systematic review of the literature to investigate these aims.

Methodology of the systematic literature review

A systematic review of the literature was used to identify, review, evaluate, synthesize, and report on the findings from peer-reviewed research (Denyer and Tranfield 2009). A five-phase process was used to establish a systematic review and is described below, and its phasing is shown in Fig. 2. The process included a pilot search and development of aims of the study, the location of research, the selection and study of literature, the analysis and synthesis of research, and the reporting of results.

Pilot search

A pilot search was conducted in order to gain an understanding of the categorical nature of existing literature. We also consulted with GR experts about the categorical topics of GRs to understand if there might be gaps in the existing literature and to develop the aims of this study (Counsell 1997).

Locating studies and relevant literature

Selecting suitable online search engines is important to identify scientific peer-reviewed research. Web of Science, Springer, MDPI, Google Scholar, and Scopus were used to identify potential articles. Papers that included "green roof" or "green infrastructure" in their keywords, title, and abstracts were located. Keywords for searches included GR material, plant, vegetation, water-use, irrigation, sustainable, ecosystem services, and life cycle.

Study selection and evaluation

We established a set of inclusion and exclusion criteria for the scope of the review. First, the time span of the existing literature was set between January 2000 and July 2022. Furthermore, since English is the common language of peer-reviewed science, only research written in English were selected. Authors worked independently to identify high-quality peer-reviewed and relevant studies. Types of literature included peer-reviewed journal articles, conference papers, book chapters, and books. The authors read the abstracts and examined the compliance of the selected studies with the aims. Afterwards, the remaining articles were evaluated in greater detail. The authors synthesized their findings and compiled the list of articles for analysis and synthesis.

Analysis and synthesis

In order to analyze the content of the selected literature, it was sorted into categories based on their association with the research questions and aims. The categories include GR ecosystem services, GR sustainability, GR life cycle, GR plant types, GR

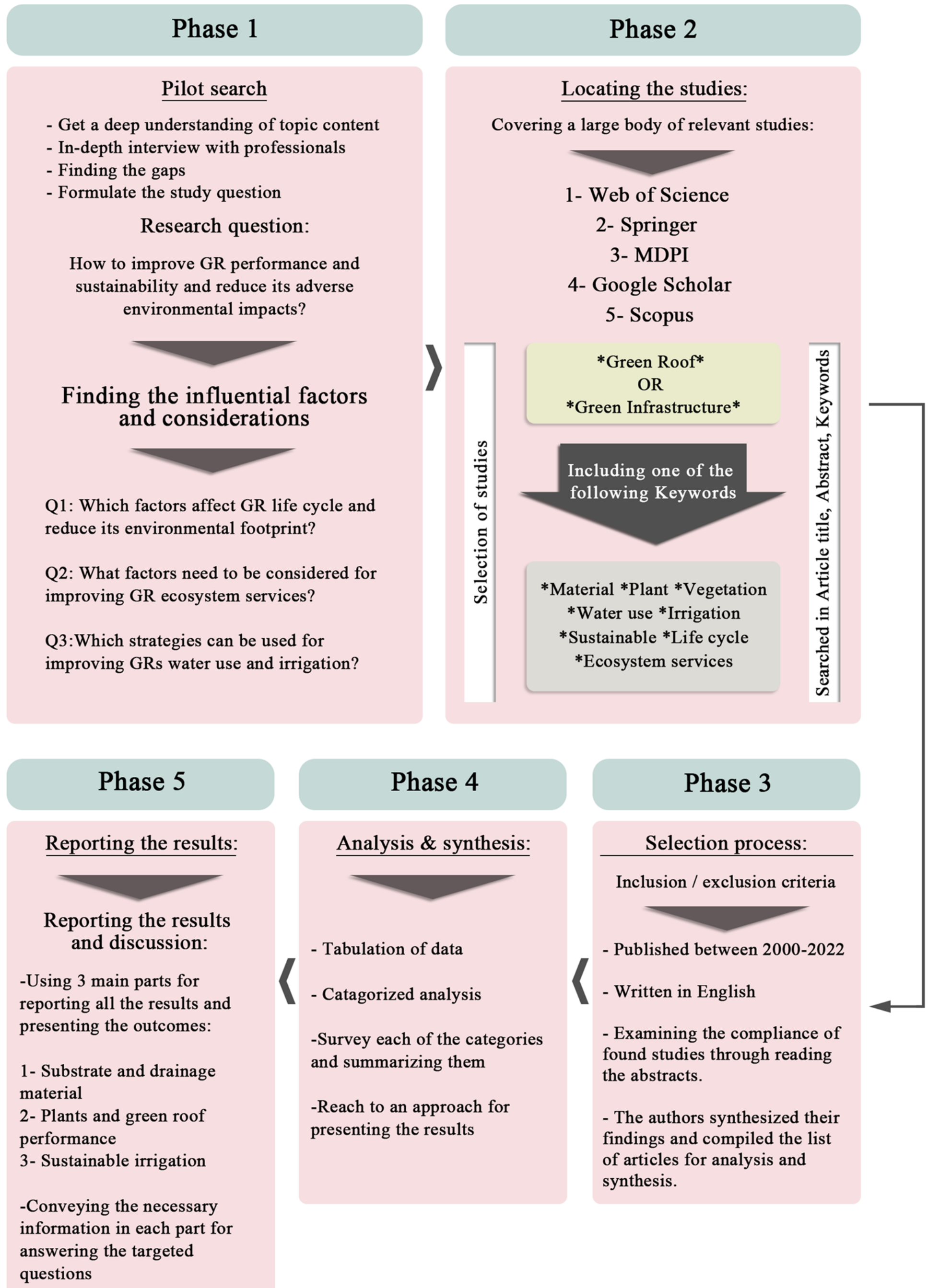

Fig. 2 Diagram of the five phases of the systematic literature review used in this study

materials, GR water-use, and irrigation. The authors then surveyed each of these categories and summarized them to reach an approach for presenting the results which targeted the questions properly.

Reporting of results

We report the results and discussion in three sections, including (1) substrate and drainage materials, (2) plants and GR performance, and (3) sustainable irrigation. This study highlights the current knowledge and suggestions of the scholars, reviews critical points and outcomes, presents influential factors and considerations, and uses figures and a table to answer the study questions.

Results and discussion

Substrate and drainage materials

The literature indicates that the selection of substrate and drainage materials for GR construction can influence the water holding capacity of the substrate, the runoff water quality, plant growth, and environmental footprints.

Material impacts on GR water holding capacity

One of the main aims of GRs is to store and slow the flow of water. Many researchers have utilized different materials in order to increase the stormwater capacity of GRs (Table 1). For instance, Vacek et al. (2017) used hydrophilic mineral wool (HMW) in the substrate layer. It was observed that HMW holds more water for longer periods than a substrate with a standard dimple membrane. However, HMW production increases adverse environmental impacts; because the HMW manufacturing process consumes relatively high amounts of energy (Vacek et al. 2017). Therefore, GR designers have faced a challenge to find suitable materials that improve GR water holding without increasing the environmental footprints GRs.

In this regard, different materials like concrete waste, biochar, mineral wool, etc. have been tested (Bisceglie et al. 2014; Cao et al. 2014; Vacek et al. 2017). Utilization of some of these materials such as concrete waste would be beneficial to reduce the consumption of natural materials, and materials like biochar would help to reach a lighter substrate layer. Table 1 presents the results of some studies that have worked on different substrate and drainage layer materials.

Material impacts on runoff quality

The leachate from GRs might contain different amounts of pollutants, and its combination with stormwater runoff turns it into a new non-point pollution source in urban areas. Substrate and drainage layer materials significantly impact the GR runoff quality (Xu et al. 2022). Whether GRs act as a sink for substances through deposition or as non-point sources of pollution depends on the substrate and drainage materials (Berndtsson et al. 2009; Alsup et al. 2011; Karczmarczyk et al. 2014; Wang et al. 2017; Baryła et al. 2018; Jennett and Zheng 2018; Qianqian et al. 2019). Additionally, the fact that water flowing from GRs has potential for non-potable uses adds to the importance of using materials that prevent water pollution (Santana et al. 2022).

In order to assess the impacts of GR substrate materials on leachate quality, many studies on different materials have been conducted. Some of them showed that some materials like Arkalyte (an expanded clay) could lead to a high concentration of heavy metals in the leachate that exceeded standards (Alsup et al. 2011). Therefore, in order to avoid the negative effects of materials on the leachate, different materials need to be tested. Table 2 provides an overview of the studies that investigated materials' impact on runoff quality.

Influence of GR substrate materials on plant growth

Selecting suitable GR materials in a way to maximize plant growth and survival is complicated due to the great influence of materials on GR plants. Furthermore, when edible plants are decided to be planted on GR, the importance of substrate layer design would be greater. Since it is indicated that plants' nutrient levels are affected by GR substrate, and Nitrates, Aluminum, Magnesium, Lead, and Selenium might lead to safety issues for producing crops like lettuce and tomato on GRs (Nektarios et al. 2022).

Therefore, many GR researchers have done studies and tested different materials to investigate the impacts of substrate materials on plant survival and physiological performance. Table 3 summarizes the results of some of these studies that tested different GR layer materials' impacts on the plants.

Materials and green roof environmental footprints

Substrate and drainage layer materials significantly affect the environmental footprints of GR life cycle (Table 4) (Gargari et al. 2016; Koroxenidis and Theodosiou 2021). Generally, to avoid an unnecessary contribution of additional environmental pollution and greenhouse gases (GHGs) emissions, long-distance transportation of materials must be avoided, when local materials are available (Lira and Sposto 2016). In addition, material sourcing that requires high energy consumption, water consumption, and waste production as part of their manufacturing must be avoided. For example, in order to show adverse environmental impacts of the manufacturing of some materials for GRs, Bianchini and Hewage (2012) analyzed air pollution attributed to GR material manufacturing processes. The study demonstrated that air pollution through the polymer production process can be balanced by GRs in 13–32 years (Bianchini and Hewage 2012). They suggested that there is a need to replace current GR materials with more environmentally friendly and sustainable products.

Using local materials is recommended to avoid environmental pollution (Eksi et al. 2020). One example of sustainable sourcing of materials is GR on the EcoCenter education building at Heron's Head Park in San Francisco, California (Dvorak and Drennan 2021). Designers sourced stone for a rooftop pond for wildlife, and the gravel edging for the entire GR, from a gravel quarry less than 1 km away. Additionally, the substrate on the GR of a kitchen house at the Slide Ranch (north of San Francisco) is made entirely from gravel, sand and soil found on the property (Dvorak and Drennan 2021). Because the site had appropriate materials to assemble a suitable substrate, no offsite delivery of materials was needed.

Table 1 Influence of substrate and drainage layers materials on stormwater retention performance of GRs

References	Aim of study	GR materials	GR layer	Summary of results
Bisceglie et al. (2014)	Evaluation of autoclaved aerated concrete as lighting material in the structure of a GR	Waste of granular autoclaved aerated concrete	Substrate	222.62% of the mass of water was absorbed by autoclaved aerated concrete waste used in a GR
Cao et al. (2014)	Assessing the effects of biochar on GR properties	Biochar	Substrate	Biochar was added to GR substrates at 0, 10, 20, 30, and 40%, v/v. At 40% biochar, an additional 2.3 cm rainfall/cm area could be retained in 10 cm deep substrates, and due to lighter substrate, an extra 1.5 cm/m^2 of the substrate could be installed
Vacek et al. (2017)	Investigating the suitability (and tenability) of individual materials in the context of assessed SIGR assemblies' total environmental impacts	Hydrophilic mineral wool (HMW)	Substrate	HMW can hold more water for longer periods than a substrate with a standard dimple membrane, but HMW production (due to high energy consumption) increases environmental impacts
Anna (2019)	Assessing the influence of the drainage layer on the GR water retention performance	Leca®, quartzite grit	Drainage layer	The retention of the substrate was 48%. With a 5 cm drainage layer of Leca®, 10% higher retention was obtained, though a 10 cm layer caused 14% greater retention However, the quartzite grit drainage layer was inferior in retention ability. The 5 cm layer of quartzite grit increased the retention by only 3% and the 10 cm increased the retention by 5%
Liberalesso et al. (2021)	Assessing the effects of using rice husk as an aggregate material in GR substrate	Rice husk	Substrate	Carbonized rice husk improved some physico-chemical properties, like Water Holding Capacity (WHC), bulk density, and porosity. Moreover, compared to local topsoil, carbonized rice husk substrates exhibited a slightly increased average retention rate (up to 7%). For all the substrates compositions with different proportions of natural and carbonized rice husk, the average stormwater retention rate was 77.73%
Yang et al. (2022)	Evaluating super-absorbent polymer, a material with great water absorption capacity, for improving the substrate water storage capacity	Super-absorbent polymer (SAP)	Substrate	Two types of SAPs, acrylic acid-attapulgite hybrid (A-SAP) and polyacrylate sylvite (P-SAP), were investigated. Both SAPs showed good water absorption, fertilizer protection ability, and reusability. However, P-SAP had higher water absorption, and A-SAP was better in substrate modification. After adding A-SAP, the saturation moisture content of the substrate increased about 23.8%, and the substrate infiltration rate decreased about 48.5%. In the GR with A-SAP, runoff control capacity was increased by more than 26%. Improvement of the water retention capacity increased the drought resistance of the GR plants

Table 2 Studies on the impacts of GR substrate and drainage layers materials on the GR leachate quality

Reference	Aim of study	GR materials	GR layer	Summary of results
Molineux et al. (2009)	Characterizing recycled waste materials as an alternative for GR growing media	Clay and sewage sludge, paper ash, and carbonated limestone	Substrate	After analyzing the leaching quality, it was confirmed that the created substrates performed within legal leachate limits for drinking water. As they can be a local source, these materials have the potential to improve GRs both economically and environmentally
Alsup et al. (2011(	Evaluation of leached metals from GR substrate samples made from Arkalyte and pine bark	Arkalyte, pine bark	Substrate	It was shown that Cd, Pb, and Zn concentrations in the leachate samples exceeded USEPA (USEPA 1999). Due to the high concentration of Pb in Arkalyte (more than 257.5 mg kg DW^{-1}), they suggested that Arkalyte significantly affect the Pb concentration
Teemusk and Mander (2011)	Comparing runoff quality from GR and modified bituminous roof	Rock wool, light-weight aggregates, humus, clay	Substrate	When rain and runoff were moderate, values of BOD, COD, and concentrations of total P and N were greater on the bituminous roof. During heavy rain events, components were less concentrated and more nitrates, and phosphates were washed off the GR. All components were greater for the GR during snowmelt
Carson et al. (2012)	Evaluating the applicability of waste and recycled materials for GR substrate	Drywall, glass, concrete, lumber clippings and roof shingles, compost made of kitchen scraps (organic content)	Substrate	Concrete aggregates alter the pH to 10.6, which is above acceptable limits. Substrates from roof shingles, lumber cuttings and drywall show potential in reducing roof loads
Bus et al. (2016)	Investigating the impacts of the drainage layer made of reactive material Polonite® on the water retention and P-PO_4 concentration of the runoff	Polonite®	Drainage layer	One way to limit P concentration in runoff from GRs is to underline the substrate with P-reactive material as a drainage layer. The 2 cm layer of Polonite® was efficient in reducing P outflow from GR substrate by 96%. Also, water retention ability increased for the substrate underlined by the Polonite® layer
Chen et al. (2018)	Assessing the influence of recycled glass and different substrate materials on leachate quality and plant growth	Recycled glass materials	Substrate	The substrate with recycled glass performed well in the neutralization of acid rain. The N concentration in each tested substrate was different. Also, The COD was significantly affected by the substrate materials. The average COD in the substrate with recycled glass was less than 20 mg O_2/L

Table 2 (continued)

Reference	Aim of study	GR materials	GR layer	Summary of results
Araújo de Almeida and Colombo (2021)	Evaluating the performance of different GRs' substrates made from green coconut fiber or sugarcane bagasse with humus	Humus generated from vermicomposting and sugarcane bagasse or green coconut fiber	Substrate	The physico-chemical analysis showed that the six types of substrates that were studied had appropriate field capacity, fine nutritional properties and pH suitable for plant nutrition. By comparing the substrates produced from green coconut fiber with those from sugarcane bagasse, it was found that the substrate with sugarcane bagasse had nitrogen content closer to the range reported as ideal. All of the substrates showed suitable physical stability

To select suitable materials for substrate and drainage layer, GR designers need to consider all the aspects that are influenced by the selection of GR materials. They need to select the materials that improve GR performance and reduce its environmental footprints. For example, recycled and renewable materials have the potential to reduce the carbon footprint of GRs by 73% (Tams et al. 2022); however, it is indicated that some recycled materials can cause water contamination (Chen et al. 2018). Accordingly, assessing the results of previous studies on different materials is an important step in the material selection process to reach sustainable GR.

Plants and green roof performance

One of the most critical aspects of establishing ecosystem services on GRs is the selection of suitable plant forms and taxa. Among the reviewed studies, the type of plants, their form, and kinds used on GRs impact GR ecosystem functions (Lundholm et al. 2010; Lundholm and Williams 2015; Xie et al. 2018) and can significantly change GR performance. Figure 3 illustrates the frequency of different GR functions reported in our chosen studies. The effect of plants on energy performance is the most frequently studied function. Other important functions include carbon sequestration, water retention, purification of water, and support of biodiversity.

Carbon sequestration potential

The ability of plants to sequester carbon is multifactorial. Different traits and environmental determinants are involved, such as how plants use water, air temperature, and relative humidity. Due to difficulties in measuring such traits on live GRs, studies were conducted under controlled conditions. In a review on influential factors that affect carbon sequestration on GRs, Wan Ismail et al. (2019) identified sixteen influential factors that affect carbon sequestration on GRs.

GR plants assimilate carbon through photosynthesis and return some of it to the atmosphere through respiration (Kavehei et al. 2018; Shafique et al. 2020). Several studies (Chen 2015; Heusinger and Weber 2017; Cascone et al. 2018) have investigated different plant species and examined the carbon sequestration potential of different plants. Some plants sequester more than others. Grasses for example, offset more CO_2 emissions during the life cycle of GRs (Kuronuma et al. 2018) and were found to reduce a building's carbon footprint by about 26 kg/m^2 (Seyedabadi et al. 2021). A study (Kuronuma and Watanabe 2017) indicated that physiological and morphological traits of vegetation types have a considerable effect on the carbon sequestration of GRs. In a study, Kuronuma et al. (2018) calculated the total annual carbon sequestration of three grass species and

Table 3 Influence of GR substrate materials on plant growth

Reference	Aim of study	GR materials	GR layer	Summary of results
Mickovski et al. (2013)	Assessing the viability of using recycled construction waste in the substrate mix for extensive GRs	Insert construction waste materials	Substrate	The substrate mix containing recycled construction waste materials supported plant growth, was resistant to erosion and slippage, and provided good drainage
Young et al. (2014)	Assessing the impacts of GR substrate components on plant growth and plant physiological performance	small or large brick, conifer bark or green waste compost organic matter, and polyacrylamide water absorbent gel	Substrate	Eight substrates with different components were built. Substrates with large brick had 35% lower WHC than small brick, which led to 17% less shoot growth and a 16% increase in root-shoot ratio. Shoot growth and root growth were 32% and 13% more in the substrate with green waste compost compared to bark. They also showed that adding polyacrylamide water absorbent gel caused 24% more substrate WHC, which increased the shoot growth by 8%
Molineux et al. (2015)	Determining whether different aggregates can provide satisfactory growing conditions for perennial plant species	Construction waste materials like: crushed red brick, crushed yellow brick, clay pellets, paper ash pellets, Carbon8 pellets, Superlite	Substrate	Some materials like clay pallets showed an increase in plant coverage and more plant species than any other substrate. It was found that recycled materials are suitable constituents of growing media for GRs, and they may improve GR resilience
Eksi et al. (2020)	Assessment of recycled or locally available materials as GR substrates	Recycled materials: crushed concrete, crushed bricks, sawdust, and municipal waste compost Locally available: lava rock, pumice, zeolite, perlite and sheep manure Organic content: municipal waste compost and sawdust-sheep manure mixture	Substrate	Twelve-substrate mixtures by using these materials were prepared. Pumice and perlite-based substrates amended with municipal compost outperformed other substrate mixtures in plant growth, plant stress, chemical and physical properties
Vannucchi et al. (2022)	Evaluation of drought and nutrient availability impact on the plant development	pelletized paper sludge, compost from municipal mixed waste, and Vulcaflor	Substrate	Twelve modules of extensive GR were set up in Pisa, Italy, with substrates composed of pelletized paper sludge, compost from municipal mixed waste, and Vulcaflor, which each substrate had a different level of nitrogen content. It was indicated that substrates' nitrogen content affected the plant composition, and limited nitrogen in substrate increases the plant functionality diversity. Substrate nitrogen scarcity caused the development of stress-tolerator annuals, increasing the biodiversity in the rainy-cool season

Table 4 Examples of studies on sustainable GR materials for reducing the environmental footprints

References	Aim of study	GR material(s)	GR layer	Summary of results
Brenneisen (2006)	Pioneer study that evaluated the use of local natural materials (sand, gravel, rock) for GR substrates and benefits for biodiversity	Local stone, gravel, sand, soils, branches/wood	Substrate	By varying the particle size, substrate depth and addition of natural materials to the GR, local wildlife will be attracted and make use of GRs
Matlock and Rowe (2016)	The study compared the use of crushed porcelain and foamed glass with heat-expanded shale in the substrate. Assessed differences in plant growth, thermal regulation and substrate moisture	Crushed porcelain and foamed glass	Substrate	Crushed porcelain and foamed glass retained more moisture and cooled substrate temperatures and had lower daily temperature variation (2.8 to 18.1 °C) compared to expanded shale (4 to 34 °C)
Farías et al. (2017)	The study examined the impacts of sieved wastes generated from the brewing industry on light-weight aggregates manufactured with clay	Sieved waste (Bagasse, diatomaceous and wastewater treatment plant sludge)	Substrate	The new aggregate had low bulk density, increased water absorption and porosity, and showed significant insulating properties. These results show its suitability for GR
Luo et al. (2015)	The study evaluated the carbon sequestration capacity of sewage sludge used in the substrate of GR	Sewage sludge	Substrate	Carbon storage of the mixed-sewage-sludge substrate (MSSS) was 13.15 kg C m^{-2}, and local-natural soil was 8.58 kg C m^{-2} on the GRs. The average carbon sequestration of MSSS was 3.81 kg C m^{-2} $year^{-1}$, and for local-natural soil, it was 3.89 kg C m^{-2} $year^{-1}$. Therefore, the MSSS could be considered as a potential material for carbon sequestration
Fan et al. (2020)	The study assessed the carbon sequestration of GRs when using Waste Building Material Substrate (WBMS) as GR substrate material	Waste building material	Substrate	The annual mean carbon sequestration of the WBMS was 1.8 times higher than local natural soil. WBMS can be considered an environmentally friendly option
Nagase (2020)	The study investigated the utility of reused materials as a potential alternative for the commercial substrate and drainage layers	Substrate: cocopeat Drainage layer: commercial GR drainage layer, bamboo stems, bamboo node, PET bottle caps, and PET bottle bottoms	Substrate; drainage layer	Reused materials were observed to function acceptably as commercial GR materials in the drainage layers. Some reused materials, such as the PET bottle caps and bamboo nodes, caused higher final plant coverage than commercial drainage layers in cocopeat
Almeida et al. (2019)	The study evaluated a GR with a cork board drainage system with polyethylene membranes	Corkboard	Drainage and water storage layer	When wet and dry, corkboard provided higher insulation capacity than conventional polyethylene membranes

Table 4 (continued)

References	Aim of study	GR material(s)	GR layer	Summary of results
Naranjo et al. (2020)	The study assessed GRs with drainage layers made out of recycled and reused materials	Recycled materials: rubber and trays Reused materials: PET bottles	Drainage layer	The dead load of GR with recycled and reused materials was reduced from 33 to 72% compared to natural materials in the drainage layers. Also, the performance of recycled and reused materials at reducing the maximum flow of runoff water volumes was suitable
Kazemi et al. (2021)	The study examined the heat transfer across GR systems with a drainage layer of incinerated municipal solid waste aggregate	Incinerated municipal solid waste aggregate (IMSWA)	Drainage layer	Transmissivity through the 5 cm IMSWA drainage layer is great. Hence, IMSWAs with a size of 0.7 cm had acceptable capacity to horizontally pass a great amount of water for a GR system. the IMSWA can be considered as a promising material for the GR drainage layer and improving the GR thermal resistance and insulating properties
Fabbri et al. (2021)	The study assessed the hygrothermal behavior of GRs equipped with coconut fiberboard as insulation material	Coconut fiber	Insulator	Coconut fiber was equally comparable to natural and synthetic materials. Although coconut fibers are mainly found in Asian, Mexico, South America, the preparation process for coconut fiber has a small footprint

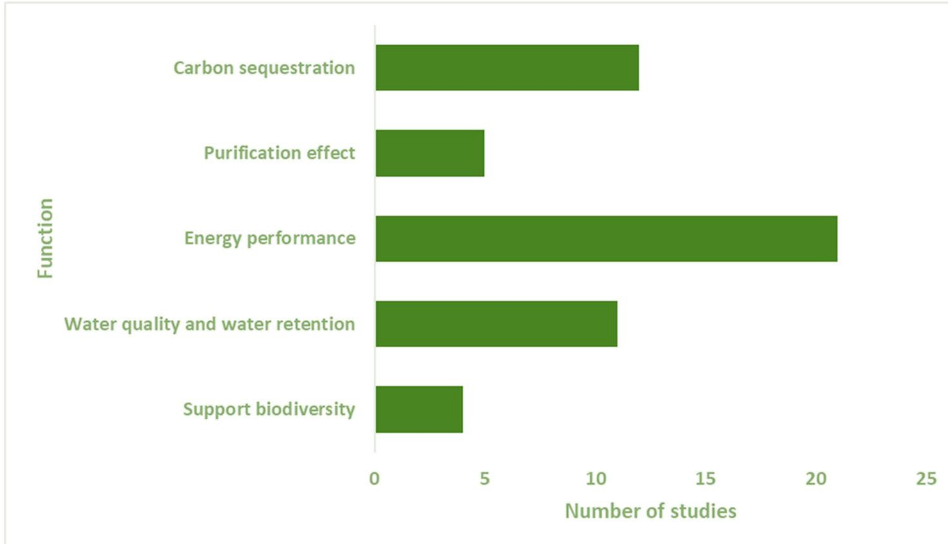

Fig. 3 Functional categories and frequency of studies investigating the roles of plants on GRs

a flowering plant and converted it to annual CO_2 sequestration, determined that *Zoysia matrella* (L.) Merr. sequestered 2.459, *Festuca arundinacea* (Schreb.) sequestered 2.754*Cynodon dactylon* (L.) Pers. sequestered 2.530 *Sedum aizoon* (L.) sequestered 1.684 kg of CO_2 per square meter per year (Kuronuma et al. 2018). Moreover, Charoenkit and Yiemwattana (2016) revealed that the GRs annual carbon storage capacity is between 0.37 and 30.12 kg/m^2, and the plant species have a significant role in this number (Charoenkit and Yiemwattana 2016).

Whittinghill et al. (2013) found the results quite remarkable on GR plant type. Plants with woody structure and higher biomass volume are able to sequester more carbon, e.g., Perennial herbs, grasses as well as ornamental landscapes (67.70 kg.m^2). In line with Whittinghill's study, Rowe (2016) also represented that plants with the greatest biomass act more effectively on carbon capturing and storing.

Getter et al. (2009) conducted a study on some *sedum*-based GRs to evaluate the natural capacity of plant selection on carbon sequestration. *Sedum album* L. stored 239 ± 53.6 C m^{-2} (g), which shows the highest rate of above-ground carbon storage among other *sedum* species. In 2015, Luo and his colleagues used sewage sludge in a GR to analyze the carbon accumulation in each selected plant species. The highest carbon storage (4.23 kg C m^{-2}) and carbon sequestration (3.85 kg C m^{-2}year^{-1}) found in *Ligustrum* × *vicaryi* Rehder. (Luo et al. 2015).

Importance of suitable plant species for air purification

The role of plant forms and different taxa of vegetation in air pollution reduction is significant. There are two main mechanisms in this function: trapping particulate matter and other pollutants physically (Yang et al. 2008) and pollution absorption into plant tissues (Clark et al. 2008; Currie and Bass 2008). Plant pollution uptake rate varies between plant taxa. For instance, Speak et al. (2012) studied the differences between diverse plant species and showed a 664% difference between plants that trapped the most particulates and the least. They expressed that this difference is mainly due to leaf characteristics like leaf hairs and ridges (Speak et al. 2012).

Moreover, a positive relationship was observed between leaf hair densities, leaf wax quantities, and plant height with particulate matter accumulation (Speak et al. 2012). The importance of these findings shows itself in the large-scale implementation of GRs. For example, Currie and Bass (2008) used the urban forest effects (UFORE) model and estimated that about 109 ha of GRs in Toronto, Canada, with herbaceous plants, would reduce 7.87 metric tons of air pollutants every year. In another research, Yang et al. (2008) showed that by implementing 19.8 ha of GRs in Chicago, Illinois, approximately 1675 kg of air pollutants could be removed in 1 year.

Plants as cooling effects and temperature reduction (energy performance)

Several studies have shown the effect of plant type on temperature reduction (Lundholm et al. 2010; MacIvor and Lundholm 2011; MacIvor et al. 2011; Sookhan et al. 2018). For the cooling effects of plants on GRs, the essential role of plants and vegetation is through evapotranspiration (Bass et al. 2003). Also, plants increase the roof albedo and reduce the urban heat island effect; in some cases, plants drop the absorbed energy in half (Sanchez and

Reames 2019). A study (Cao et al. 2019) showed that the cooling generated by the GR is related to the yield of the plants, which is strongly associated with the type of plants with the different photosynthetic and water-use strategies. In this study, C4 grasses demonstrated the highest transpiration (4.4 mm day^{-1} of *Cynodon dactylon* (L.) Pers.), which means a greater cooling effect than the C3 grasses. CAM plants contribute to the cooling effect by absorption and insulation. Moreover, in a study for investigating the energy performance of a GR, Foustalieraki et al. (2017) indicated that different plant species offer different thermal behavior on GRs and expressed that an optimum selection among different plant species is necessary to reach the best GR performance. They also showed that having plants with dense foliage (compacted leaves and/or canopy that block the path of sunlight reaching the ground) will result in more reduction in surface temperature (Foustalieraki et al. 2017).

Studies that examined different vegetation found 9.7–24% differences in substrate temperature between vegetation types, with some proofs that this differentiation increased over time as vegetation cover increased (Lundholm et al. 2010; MacIvor and Lundholm 2011; MacIvor et al. 2011, Dvorak and Volder 2013a, b). Schindler et al. (2019) compared two GRs with different vegetation types and observed a 1.5 °C temperature difference between them and expressed that high albedo, evapotranspiration, and shading are the essential factors in a GR's cooling effect (Schindler et al. 2019). Many studies (Zhou et al. 2018; Samah et al. 2020; Cavadini and Cook 2021; Grala da Cunha et al. 2021; Tadeu et al. 2021) unanimously expressed that the vegetation Leaf Area Index (LAI) significantly impacts temperature. For example, Rakotondramiarana et al. (2015) conducted a study in Madagascar Island on an extensive GR and showed that indoor air temperature decreases about 1 °C by increasing LAI from 1 to 5 (more LAI means more dense foliage) (Rakotondramiarana et al. 2015). The thermal behavior of different types of vegetation can greatly change the energy consumption of the building. Karachaliou et al. (2016), by planting shrubs and perennial herbs with diverse thermal behavior showed that different species of vegetation can cause an 11% reduction in energy consumption for heating the building and 19% for cooling the building (Karachaliou et al. 2016).

Influence on water quality and water retention

Plants also influence the quality of runoff (Rowe 2011; Hashemi et al. 2015) and stormwater reduction (Kemp et al. 2019). Gong et al. (2021) indicated that diverse plant species have different effects on nutrient loads. Aitkenhead-Peterson et al. (2011) compared the effects of different succulent species on nitrate leachate and showed an 1120% difference between the best and worst-performing. Moreover, they showed that by cultivating different types of plants in the same media, there was a striking reduction in the nitrogen and phosphorus concentrations in the runoff water (Aitkenhead-Peterson et al. 2011).

Cook-Patton and Bauerle (2012) reviewed the benefits of plant diversity on GRs and indicated that species differ in when and how they absorb nutrients and showed that through having higher plant diversity, more nitrogen was consumed efficiently than when there were monocultures. This means that the utilization of fertilizer nitrogen and the possible leaching of the nitrogen from GRs could be decreased by having diverse species on the roof (Czemiel Berndtsson 2010). Regarding plant type effect on water retention, Talebi et al. (2019) indicated that vegetation type had a greater influence on water retention than increasing the substrate storage. Maclvor et al. (2011) and Lundholm et al. (2010) conducted studies on this subject. The first one showed a 20% increase in retention in the best mixture treatment compared with the best monoculture, and the latter one found an 8.4% increase with using more species (Lundholm et al. 2010; MacIvor et al. 2011).

Use of native plants for conservation of biodiversity

One of the unique opportunities to make GRs sustainable is their potential to support local plants, plant communities, and wildlife (Brenneisen 2005; Chen et al. 2021; Dvorak and Bousselot 2021). Although alien plants on GRs can serve some forms of wildlife (MacIvor et al. 2015), native plants can serve local and migratory wildlife (Cook-Patton 2015). The composition of wildlife community and biodiversity is different between intensive GRs and extensive GRs, and studies have shown that community biodiversity is higher in intensive GRs (Coffman 2007; Nagase et al. 2018). To assess the elements and GRs' characteristics that enhance arthropod biodiversity and ecological functioning, Fabián et al. (2021) conducted a study and analyzed these characteristics. They selected 30 GRs situated in Argentina in different urbanization contexts (from small towns in semi-rural regions to large towns). They found that total species richness, total abundance of arthropods, and species richness of most functional feeding groups were positively associated with the GRs area. They also expressed that promoting high plant diversity and lessening roof isolation favored entomophagous arthropod diversity (Fabián et al. 2021).

Not only GRs are potential homes for the local biodiversity, i.e., spiders and beetles, but they also are a refuge for rare and endangered species like birds. GRs provide a safe habitat for invertebrates and vertebrates in urban areas (Brenneisen 2003; Gedge and Kadas 2005).

Current challenges and discussions

It has become clear that the GR ecosystem services rely on the plant types, and individual traits or trait combinations can influence them. However, the priority for selecting the GR plants is their survival on the GR. GRs are often planted with low water-using succulents to have a better chance of survival. These plants can tolerate shallow substrates and extremely hot and dry summers (Dvorak and Volder 2010; Rayner et al. 2016). However, because of their low water-use, these plants when compared to grasses and herbaceous perennials, do not deliver the highest stormwater retention and cooling (Azeñas et al. 2018a, b). Plants with high water-use optimize stormwater mitigation on GRs as they assist substrate drying after rainfall (Farrell et al. 2013). However, supplemental irrigation may be necessary to keep these plants thriving in some climates. Therefore, shallow depth substrates, low water availability, extreme climate events, and prolonged drought challenge designers for suitable plant selection. This selection must consider two important factors; plant survival and delivering the best GR performance. Climates with hot and dry conditions throughout much of the year may not need high functioning stormwater retention performance from GRs. Instead, cooling and shading rooftops is a primary ecosystem service.

Many researchers have worked to specify the factors related to plant survival on GR. Du et al. (2019) experimented on 15 shrub species from a range of climates and showed that plant survival was not related to water-use, drought response, or climate of origin. They suggested that plant survival on GRs is expected to be determined by a combination of physiological traits (traits like leaf thickness, roots, and stomata). Another study examined whether plant traits like succulence are related to plant survival and resulted that survival was not related to water-use, succulence, or leaf heat tolerance (Guo et al. 2021). Farrell et al. (2012) evaluated severe drought impact on the survival of five succulent species and showed that plants survived longer on the substrate with higher WHC. They expressed that increasing leaf succulence is not related to plant survival, but survival was related to reduced biomass under drought. That study showed that to maximize survival, GRs should be planted with species that have great leaf succulence and low water-use in substrates with high WHC (Farrell et al. 2012). Taking to account some fast traits, e.g., relative growth rate (RGR) and leaf area for water-use in nine native plants, showed more plasticity in water treatments (Schrieke and Farrell 2021).

Analysis of studies

An analysis was conducted on the plants investigated in "Plants and green roof performance" section to determine the trend in the GR plant studies. Most researched plant families, measured traits, and lifeform were determined.

Plant families

Eighty-six plant families have been applied in our examined studies in order to find suitable species to achieve the best performance. Three families represented the most species-rich, namely Crassulaceae (22), Asteraceae (15), and Poaceae (14) (Fig. 4).

Crassulaceae are widely distributed. This family comprises perennial herbs with fleshy leaves that are able to tolerate arid conditions, i.e., shortage of water and high temperatures. These features make the species (e.g., *Sedum*) perfect to grow on GRs. Among 20 *Sedum* species, *Sedum spurium* M.Bieb. and *Sedum acre* L. are the foremost planted taxa in reviewed research experiments, nine and eight research, respectively.

Poaceae, known as the grass family, is one the most species-rich families in the plant realm that provides diverse species with various characteristics which make them suitable for GRs.

Measured traits

Among all the plant traits, for assessing plants' influence on GR ecosystem services, most authors studied leaf area more than other traits. Leaf area is related to the relative growth rate (RGR) as well as net assimilation rate (NAR). As shown in Fig. 5, the other traits are less focused.

Heat stress is one of the challenges on GRs that influences the root that alters the water use efficiency as well as plant survival. The root vulnerability to heat stress is discussed by Savi et al. (2016) and Tomasella et al. (2022). While the crucial role of this trait is one of the main determinants of GRs performance, more investigations into this issue are recommended.

Lifeforms of plants

The lifeform of GR vegetation is one of the significant plant attributes which reveals the adaptive structure of a plant in a given habitat. Perennial herbs are the most frequent lifeform used on the GRs in research. Moreover, perennial herbs used on GRs demonstrate ground cover, which protects the surface from direct sunlight, consequently contributing to the cooling effect (Table 5).

Perennial herbs are the dominant lifeform in conducting GR experiments. To look more closely at the plant type of perennial herbs, it was forbs that represented the greatest group, followed by grass (Fig. 6). Heat and drought tolerance and having below and above groundwater storage structures are the significant features of the forbs, grass, and succulents which make them suitable and popular in GR experiments. Using multiple lifeforms in GR showed better ecosystem performance compared to monocultures (Lundholm et al. 2010).

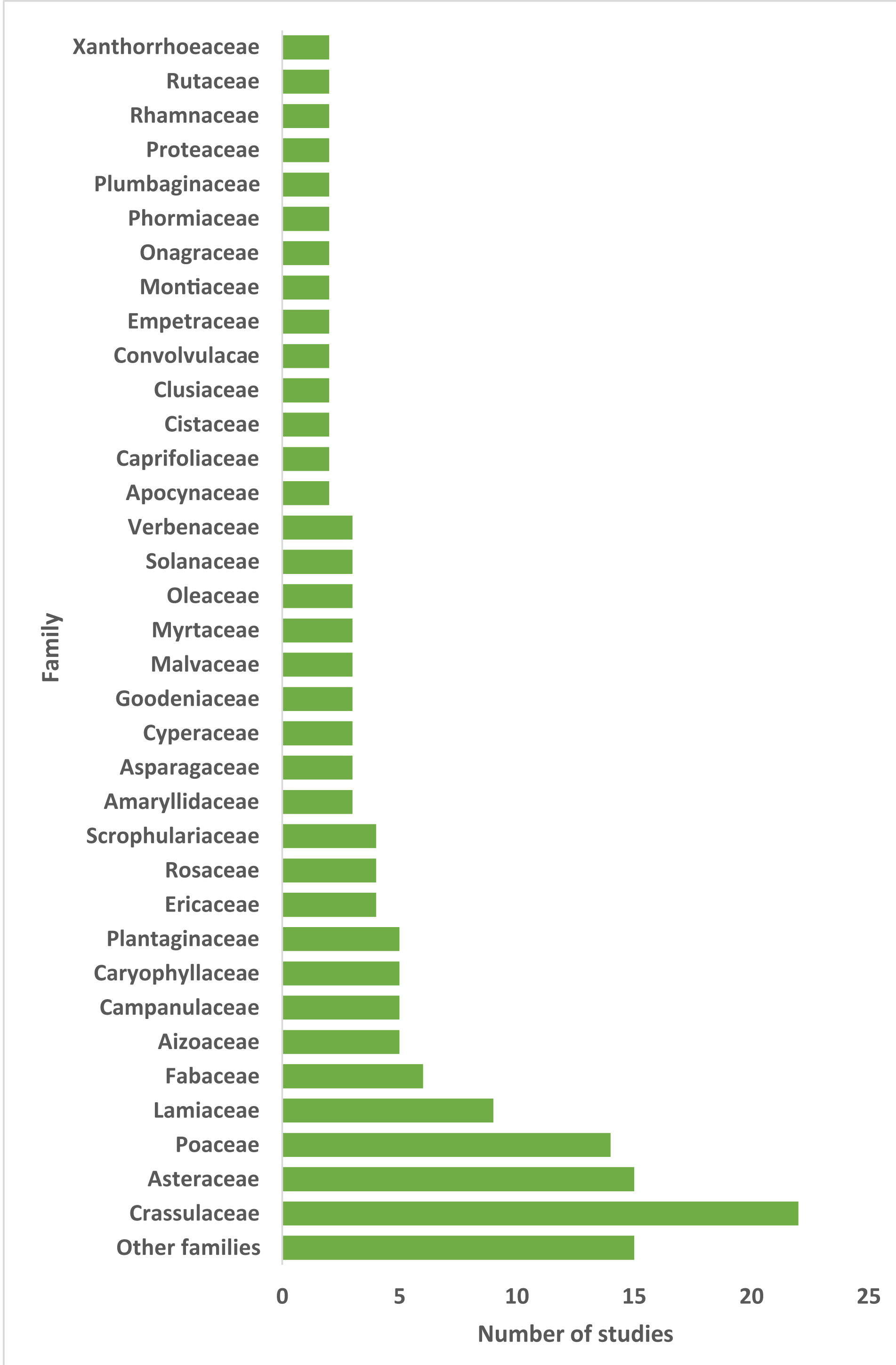

Fig. 4 The taxonomic spectrum of plant families and the number of GR studies

Sustainable irrigation

Irrigation is one of the critical aspects that must be considered for constructing and maintaining sustainable GRs. Water is the most critical aspect of life on Earth, and due to human destructive actions and climate change, there is high stress on water resources and an urgent need for water resource management. There are several different strategies and solutions for reducing water consumption. In the review of the literature, it was found that GR water-use can be reduced by using appropriate irrigation strategies (Bousselot et al. 2010; Van Mechelen et al. 2015).

In tropical areas or humid climates, it is possible to establish unirrigated GR if suitable vegetation and materials are

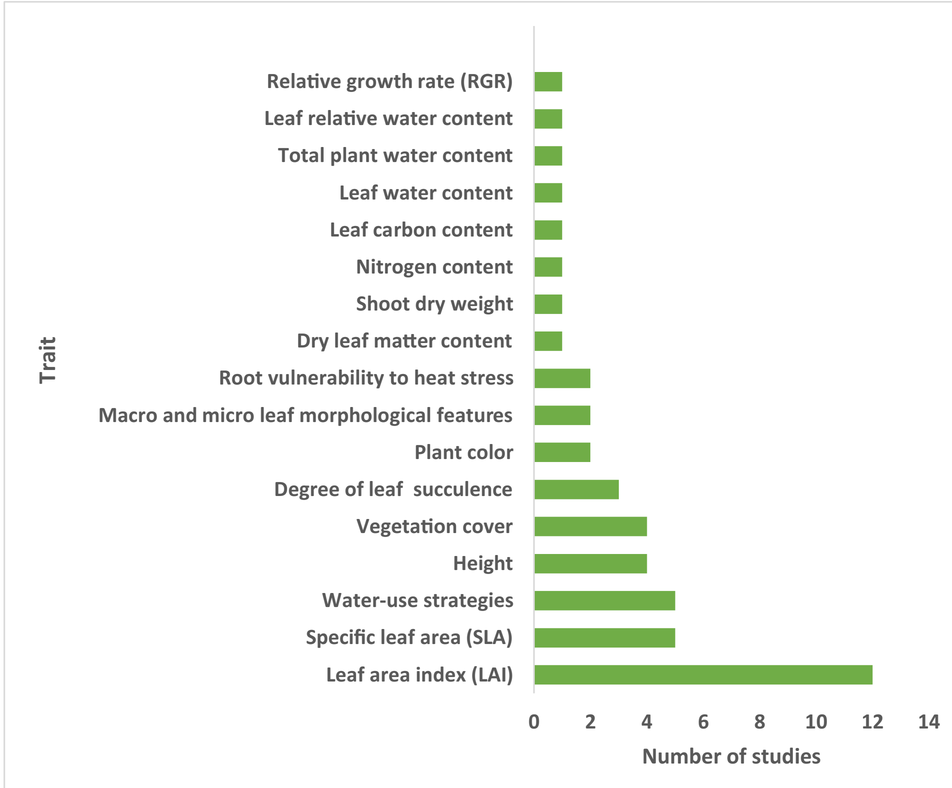

Fig. 5 Measured traits for plant selection based on the review of the literature

Table 5 Different plant lifeforms selected for GR from the research

Lifeform	Frequency of plants used for GR
Perennial herbs	194
Shrubs	107
Annual herbs	25
Trees	13
Climbers	2

selected. Criteria for selecting vegetation for unirrigated GR systems are explained in the FLL guidelines (Breuning and Yanders 2008; FLL 2018). The guidelines specify that GRs are designed to depend primarily on precipitation for their water supply but considering all types of climate, such as hot and dry climates where experiencing low precipitations, it may not be possible to depend on precipitation alone (Dvorak and Volder 2013a, b).

Therefore, there is a strict relationship between GR irrigation management and GR plants survival, and it has been indicated plant survival rate on unirrigated GRs has not been satisfying (Dvorak and Volder 2013b). Besides, some studies have shown that GR irrigation has a cooling effect and increases evapotranspiration (Wang et al. 2021a, b) and considerably improves building thermal performance (Porcaro et al. 2021; Yazdani and Baneshi 2021). A study in a semi-arid climate in Mexico showed that after irrigating GR, the maximum temperature of vegetation and substrate reduced by 6.4 and 4.8 °C, respectively (Chagolla-Aranda et al. 2017). Lin and Lin (2011) showed that a substrate that is irrigated twice a week is able to reduce the heat amplitude under the roof slab surface up to 91.6%. However, in some cases, due to the fact that water has higher thermal conductivity than air, lower heat fluxes have been reported from GRs with limited irrigation than well irrigated GRs (Azeñas et al. 2018a, b). It means that higher substrate water is not always effective in controlling evapotranspiration and providing the related cooling effect (Jim and Peng 2012).

The optimal frequency and rate of irrigation required for GRs have been investigated in various ways by several studies. For example, a study in a Mediterranean climate on extensive GRs with testing four types of plants showed that the GR water requirement ranges between 2.6 and 9 L/m^2/day, and it differs due to plant type species (Schweitzer and Erell 2014). In other studies conducted in the Mediterranean climate on the GRs water-use in summer, the water required for GR irrigation ranged from 1.96 L/m^2/day in Athena, Greece (Papafotiou et al. 2013) to 7 L/m^2/day in Rende, Italy (Brunetti et al. 2018). Pirouz et al. (2021) showed that the average water-use of GRs in the summer in humid regions is about 3.7 L/m^2/day, in the Mediterranean regions about 4.5 L/m^2/day, and in arid regions about 2.7 L/m^2/day.

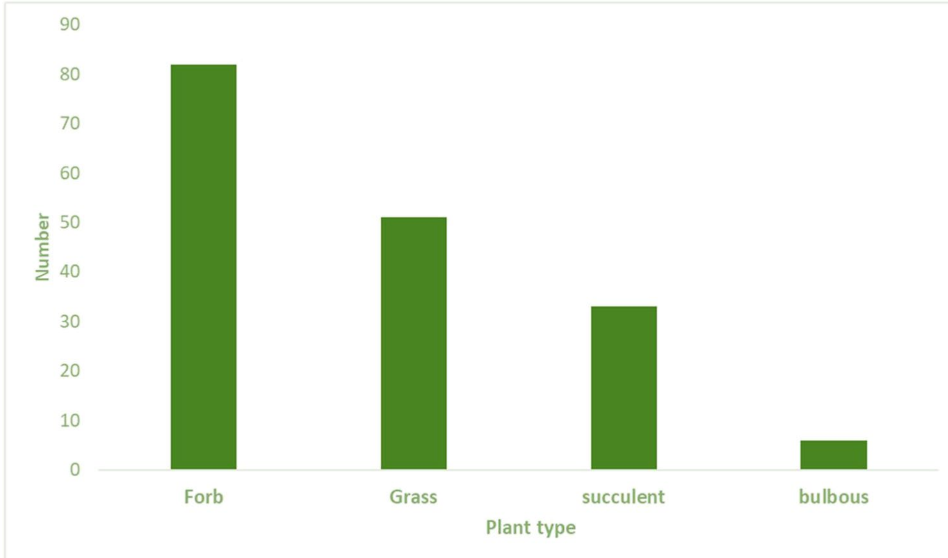

Fig. 6 Plant types of perennial herbs used in GR research

Therefore, it is necessary to know the sustainable irrigation strategies to reach maximum performance of GR with minimum water consumption. Reviewing the literature showed that GR irrigation strategies can be divided into three main sections: (1) Employing alternative sources, (2) smart irrigation and monitoring, and (3) using adaptive materials and additives that improve GR water-use.

Employing alternative sources

In recent years, it has become popular to utilize alternative water sources to avoid potable water use on GRs. This section aims to discuss and introduce suitable alternative sources to reduce potable water usage on GRs. Due to a lack of comprehensive knowledge in this section, some of the references are not GR related. In each section, literature gaps have been indicated.

Rainwater harvesting

One of the most available sources of free water that has a long history of use is harvested rainwater. The effectiveness of rainwater harvesting systems depends on the region's climate type and precipitation frequency. The quantity of rainfall affects the degree of rainwater-use. Rainwater harvesting has gained popularity for GRs in some regions (Almeida et al. 2021; Burszta-Adamiak and Spychalski 2021). Different studies proposed multiple approaches for rainwater harvesting, such as rainwater cisterns or tanks, treatment trains, and constructed wetlands (Hardin et al. 2012; Coutts et al. 2013; Chao-Hsien et al. 2014; Hafizi Md Lani et al. 2018; Kucukkaya et al. 2021). For example, Coutts et al. (2013) studied the potential of water-sensitive urban design (WSUD) (WSUD is an approach to design urban areas to make use of valuable resources like rainwater). They demonstrated that WSUD provides a mechanism for retaining water through stormwater harvesting and can be a dependable source of water across Australian urban environments for landscape irrigation. In semi-arid regions, where rainfall is infrequent, many GRs in western North America have made use of harvested rainwater and have had success (Dvorak and Skabelund 2021).

Some researchers have suggested blue-green roofs as a way for using rainwater for irrigating. Generally, blue-green roofs have an extra water retention layer that allows more stormwater to be stored so that the reservoir can act as a source of water for the GR through capillary rises (Busker et al. 2022). Moreover, Droz et al. (2021a, b) showed that blue-green roofs provided the most services with the lowest number of trade-offs and expressed that the GR system type is the most impactful on ecosystem services.

Chao-Hsien et al. (2014) examined the primary design factors of a rainwater harvesting system for GRs and conducted a case study on a university building in Keelung, Northern Taiwan. For this building and climate, the optimal tank volume was 9.41 m^3 and the potable water replacement rate and probability of exceedance were 92.72% and 88.76%, respectively.

Besides being a sustainable source for GR irrigation, harvesting rainwater reduces erosion and stormwater pollution and helps reduce flooding in dense urban areas (Hardin et al. 2012; Islam et al. 2013). It is necessary to mention that rainwater harvesting systems need maintenance. Some studies have observed poor microbial water quality (Al-Batsh et al. 2019; Dissanayake and Han 2021). Other studies have shown that suitable treatment and disinfection methods can convert harvested rainwater into drinking water (Alim et al. 2020).

Greywater recycling and green roof irrigation

Greywater is wastewater that includes water from baths, showers, hand basins, washing machines, dishwashers, and kitchen sinks, excluding streams from toilets (Eriksson et al. 2002). Some sources exclude kitchen wastewater from the other greywater streams (Al-Jayyousi 2003; Wilderer 2004). Greywater use on GRs is an alternative and sustainable method for GR irrigation. It is more complex and more expensive than rainwater harvesting because it requires a pipe system separate from blackwater. Also, one of the advantages of greywater is the expanding place of its generators in everyday use and its availability.

Several studies suggested using greywater for GR irrigation (Mahmoudi et al. 2021). Chowdhury and Abaya (2018) carried out an experimental study of greywater-irrigated GR systems in Al Ain, United Arab Emirates. By monitoring the greywater influents and the GR effluents from two intensive and two extensive GRs irrigated with greywater, they observed the changes in the greywater quality and organic treatments (Chowdhury and Abaya 2018). They showed that treated greywater effluent from the GRs met the local standards for recycled wastewater-based irrigation in parameters like pH, electrical conductivity, salinity, and total dissolved solids (TDS). For example, the values of mean TDS in the effluents from the extensive and intensive systems were ~ 1.7 g/L and ~ 1.3 g/L, respectively. They expressed that TDS removal was greater in intensive GRs due to the greater depth of the soil–sand medium in the intensive GR. One building in Seattle, Washington (Bullitt Center), uses harvested water for interior use, then uses a constructed wetland GR as a final treatment of the greywater. Research on this GR suggests that there is a proper balance between the sourcing of water and cleaning capacity of the vegetation on the GR (Dvorak and Rottle 2021). On the base floor of this building, a 212-m^3 cistern is located to collect 69% (128,000 gallons) of the rooftop runoff, and the stored water is used for potable and non-potable uses. After use in the building, the water is pumped on the GR through a series of drip lines so that the plants can absorb the nutrients. Then the water is collected and pumped through the system several more times to the point that the nutrients have been absorbed (Center 2013; WBDG 2016).

Thomaidi et al. (2022) conducted an experiment in Lesvos island, Greece, to assess the use of GRs as modified shallow vertical flow constructed wetlands for greywater treatment in buildings. They investigated the effects of different design parameters such as substrate material (perlite or vermiculite), substrate depth, and plant species (*Geranium zonale* L., *Polygala myrtifolia* L., or *Atriplex halimus* L.) on the effluent quality. The GRs planted with *Atriplex halimus* and with 20 cm of vermiculite substrate had the best BOD (91%), TSS (93%), COD (91%), and turbidity (93%) average removal efficiencies. They showed that substrate depth is a highly influential factor in greywater treatment and observed when the substrate depth was decreased to 10 cm the average removal efficiencies were reduced to 60–75%. Also, the recirculation of a portion of the effluent in the influent increased the turbidity, organic matter, and nitrogen removal.

Liu et al. (2021) expressed that GRs irrigated with domestic wastewater satisfied GR irrigation requirements and improved the urban wastewater treatment system. Through using greywater for GR irrigation and planting different plant species, they showed that GRs can be considered as a nature-based solution for domestic wastewater treatment and revive the urban water resource (Liu et al. 2021). Using greywater for GR irrigation can have multiple benefits. Yet, there were no reported adverse effects on plants due to greywater for irrigation (Agra et al. 2018). In a study for indicating the plants' response to greywater irrigation, Yalcinalp et al. (2019) compared two different greywater models and tap water for GR irrigation. They showed that the use of greywater provides more positive effects on plant growth compared to that of tap water. Also, utilizing greywater can reduce the irrigation costs of the GR (Yalcinalp et al. 2019). Hence, by using greywater in GRs, it is possible to sustain plant growth, reduce the use of potable water, and reduce demands on municipal wastewater treatment plants (Xu et al. 2020). One challenge with the use of greywater on GRs is the testing and monitoring of water quality to ensure that water quality is acceptable for local use. Special permits or permissions may be required to secure the use of greywater based on individual local authorities and guidelines.

Innovative sources for water consumption and irrigation purposes

Atmospheric water harvesting (i.e., fog) is one of the unique sources that has caught the attention of researchers (Bagheri 2018; Kim et al. 2018; Tu and Hwang 2020; Zhou et al. 2020). Water harvesting methods from the atmospheric fog and dew have been found to be useful in different applications (Jarimi et al. 2020). Several studies (Beysens et al. 2007; Tomaszkiewicz et al. 2015) indicated that dew water collection could serve as a potential water source in tropical, high humid, and specific climates. Also, some studies showed that dew water harvesting is a sustainable and suitable source for agriculture purposes. Tomaszkiewicz et al. (2017) in Beiteddine, Lebanon (semi-arid climate), assessed the potential of dew harvesting during the dry season for agriculture purposes. They showed that a dew harvesting system with a size of 2 m^2 could produce 4.5 L/month, which is sufficient for the irrigation of tree seedlings.

In an innovative approach to improve GR water use efficiency, Pirouz et al. (2021) assessed dew and fog harvesting potential during the dry season. The average potential for fog in humid regions is 1.2 to 15.6 L/m^2/day and for dew is 0.1 to 0.3 L/m^2/day, in the Mediterranean regions for fog is 1.6 to 4.6 L/m^2/day and for dew is 0.2 to 0.3 L/m^2/day, and in the arid regions the potential for fog is 1.8 and 11.8 L/m^2/day and for dew is 0.5 to 0.7 L/m^2/day. The study's conclusion demonstrated that fog harvesting could provide the total water requirement of the GRs. Dew harvesting by PV (photovoltaic) panels could provide 15 to 26% of the water requirements (Pirouz et al. 2021). However, there is a need to conduct practical studies in different climates to investigate the potential of atmospheric water harvesting for GR irrigation.

Smart irrigation and monitoring

One of the direct ways to manage water use and conservation on GRs is the use of smart irrigation technology. Several studies on GRs with smart irrigation systems indicated that water requirements can be calculated by evapotranspiration data (Bandara et al. 2016) and precipitation information (Stovin et al. 2013) or by directly observing the substrate moisture with sensors (Jim and Peng 2012). When substrate moisture content drops below a certain level, the irrigation system can be programmed to run. When sufficient irrigation has been delivered or in the case of rainfall, the irrigation system is prevented from running a cycle so there will be no excessive watering and superfluous supply. This method was applied by Tomasella et al. (2022) on shrub vegetated Mediterranean extensive GRs, and results suggested that maintaining substrate water level at a certain threshold was significantly effective in optimizing GR benefits, reducing water consumption and favoring plant establishment. Besides, significant water savings were reported compared to the common irrigation timer maintenance method.

Other methods include a study (Gu et al. 2021) where a neural network model is proposed in order to learn from a process-based agricultural systems model. This process determines irrigation timing and amount by predicting soil moisture. In a similar study, Tsang and Jim (2016) used artificial intelligence modeling to optimize GR irrigation efficiency, and for simulating changes in soil moisture, used fuzzy logic and an artificial neural network. They indicated a 20% reduction in water-use and improvement in plant coverage by applying this method.

Using adaptive materials and additives that improve GR water-use

Designing GRs and selecting the appropriate materials and vegetation type can be done in a way to reduce irrigation requirements and improve GR water-use. Increasing the WHC potential of the substrate layer would greatly improve the irrigation requirement of GRs. Some materials, as mentioned in "Material impacts on GR water holding capacity" section, have the ability to increase the WHC.

In a study, Kanechi et al. (2014) by testing and comparing three different substrates (amended soil, turf mat, furnace bottom ash), showed that amended soil, due to the presence of decomposing organic matter, had higher water and nutrient holding capacities. Paradelo et al. (2019) investigated WHC in modified compost-based substrates and showed bentonite increased the WHC of the substrates. Some authors worked on some additives, such as hydrophilic gels, to improve the WHC (Williams et al. 2010; Sutton et al. 2012). Savi et al. (2014) assessed a GR performance amended with hydrogel and showed that hydrogels considerably increased the water content of substrate at saturation and water available to vegetation. However, increasing the water holding potential of GRs must be done with great attention to the roof's capability to sustain heavier loads. Because heavier loads on roofs could cause damage to buildings with weak or old structure. Other research shows how the water retention layer can play an essential role in sustaining soil moisture (Tan et al. 2017), and through retaining water, it can reduce the irrigation requirement. A study by Roehr and Kong (2010) showed that GR summer irrigation decreased from 54.4 to 8.6 mm in Vancouver, Canada, by adding a water retention layer (Roehr and Kong 2010).

However, the crucial role of plant type cannot be neglected in irrigation (Zhang et al. 2021). Some plant types, such as mosses, have high-water retention and can be beneficial for the soil moisture content (Elumeeva et al. 2011). Roehr and Kong (2010) expressed that if an average roof area of 3700 m^2/ha is assumed in Shanghai, GRs with low water-use plants could potentially reduce stormwater runoff by 903.2 m^3 per year and by using high water-use plants this number reaches 1806.7 m^3 per year (Roehr and Kong 2010). A study in Portugal for optimizing the water-use of GRs suggested using native plant species due to better tolerance against drought (Paço et al. 2019). This study showed that the mixture of mosses and vascular plants were an interesting solution for water-use improvement since mosses had a large water retention capacity, and vascular plants can use the retained water (Paço et al. 2019). Therefore, the selection of suitable plants and materials influences the GR water requirement.

Conclusion

Due to the growing popularity of GRs and various attempts to improve different aspects of GRs, it is crucial to learn and know how to build sustainable GRs to maximize their ecosystem services and reduce their negative environmental impacts. In order to achieve these purposes, considerations and influential factors must be known, and the role of each of them needs to be distinguished. By following the review methodology and its phases, this study focused on three main topics: (1) substrate and drainage materials, (2) plants and GR performance (biological GR components), and (3) sustainable irrigation. In each of these three topics, valid points are presented to be considered for building sustainable GRs, with enhanced performance. The main points include:

1) GR materials (Substrate and drainage layer)

- The key to reach sustainable GRs is using sustainable materials in different layers of GRs. Substrate and drainage layer materials affect the GR performance and influence the adverse environmental impacts. Substrate and drainage materials significantly affect stormwater retention potential, leachate quality, and plant survival and also determine GR environmental footprints.
- The use of recycled, reused, or locally available materials can reduce GR environmental footprint and improve GR's life cycle. However, the influence of these materials on GR performance must be examined carefully. In some cases, using the materials that improve GR sustainability results in a reduction in GR performance.
- Transportation of GR materials is another issue that can cause environmental pollution and CO_2 emissions. The solution is using locally available materials. However, the GR supply market has not developed in some regions, and demand for more research and more suitable local materials is rising.

2) Plants on GRs

- GR vegetation is a critical element of the overall performance of the GR. Different forms of plants have different potentials in CO_2 sequestration, air pollution absorption, temperature reduction, stormwater retention, local habitat provisions, and improving water quality and consumption. However, plant survival must not compromise in the strive for improving GR performance. It has shown that having higher plant diversity would benefit GR sustainability.
- Vegetation LAI has an important effect on temperature reduction, as an increase in LAI can offer more summertime cooling and reduce the urban heat island effect. In ecoregions where there are few plants with large leaves, it may be possible to cluster plants or use different forms of plants to shade the rooftop.
- Lifeform is one of the significant plant attributes which reveals the adaptive structure of a plant in a given habitat. Based on the conducted review, perennial herbs are the most frequent lifeform for selected vegetation on GRs. They do not need to be replanted each year and are heat and drought tolerant.

3) Sustainable irrigation

- A critical aspect of a sustainable GR is managing irrigation by avoiding excessive use of potable water. Irrigation is vital for plant survival and has a major influence on GR performance (i.e., temperature reduction).
- Several ways to improve GR irrigation include employing alternative water sources, monitoring and smart irrigation, adding additives, and using materials that increase WHC. Lack of knowledge about sustainable irrigation has caused many GRs to use the traditional irrigation method and stress limited water sources.
- Using alternative irrigation sources like rainwater, greywater, and atmospheric water, besides satisfying water-use of GRs, can be considered as sustainable water sources for other purposes. Smart irrigation and using sensors in GRs reduce the amount of irrigation requirement. Greywater shows promise for satisfying GR irrigation demand since it has no adverse effect on GR performance and can benefit plant growth. Many projects have used GR for greywater treatment and have had success.
- Considering the potential of some vegetation and some substrate and drainage materials to reduce the water-use of GR is important. Materials and plant species have the ability to increase WHC so that little irrigation will be needed. Also, some additives are introduced by researchers that have the ability to reduce the water-use of GRs by increasing WHC.

The results of this study can be useful to GR designers and legislators to establish and make use of knowledge to support regulations that follow common goals and help build sustainable GRs with better performance. This paper addresses the current lack of knowledge and challenges of building sustainable GRs. It may also be useful to help other GR researchers better understand research gaps and needs for future studies.

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Declarations

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