coatings

Review

State-of-the-Art Green Roofs: Technical Performance and Certifications for Sustainable Construction

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Abstract: Green roof systems, a technology which was used in major ancient buildings, are currently becoming an interesting strategy to reduce the negative impact of traditional urban development caused by ground impermeabilization. Only regarding the environmental impact, the application of these biological coatings on buildings has the potential of acting as a thermal, moisture, noise, and electromagnetic barrier. At the urban scale, they might reduce the heat island effect and sewage system load, improve runoff water and air quality, and reconstruct natural landscapes including wildlife. In spite of these significant benefits, the current design and construction methods are not completely regulated by law because there is a lack of knowledge of their technical performance. Hence, this review of the current state of the art presents a proper green roof classification based on their components and vegetation layer. Similarly, a detailed description from the key factors that control the hydraulic and thermal performance of green roofs is given. Based on these factors, an estimation of the impact of green roof systems on sustainable construction certifications is included (i.e., LEED—Leadership in Energy and Environment Design, BREEAM—Building Research Establishment Environmental Assessment Method, CASBEE—Comprehensive Assessment System for Built Environment Efficiency, BEAM—Building Environmental Assessment Method, ESGB—Evaluation Standard for Green Building). Finally, conclusions and future research challenges for the correct implementation of green roofs are addressed.

Keywords: green roofs; biological coatings; hydraulic performance; thermal performance; sustainable construction certification; LEED; BREEAM; CASBEE; BEAM; ESGB

1. Introduction

Due to its multiple benefits, biological coatings on buildings (i.e., green roofs and walls) were used by different human civilizations [1,2]. According to the scientific community, there is testimonial evidence of the use of biological coatings on Babylon's Hanging Gardens and Babel Tower [2–4]. Similarly, religious buildings called "Ziggurats" were constructed in Mesopotamia using plant growth on their building surfaces most probably to reduce heat interchange with the environment [3]. Biological coatings were also part of vernacular architecture in Scandinavia. For instance, in Norway, green roof systems are still used as a thermal isolation system [5].

Even when green roofs were present on the major buildings of the ancient world, their use on contemporaneous architecture reappeared only in the 20th century with the Swiss architect Le Corbusier who included them among modern architecture principal elements [6]. In fact, he stated that "the garden terrace will be the reunion place preferred by citizens and it will also mean the recovery of the built surface from the city". In this sentence, the preoccupation that exists since then about the accelerated urban development is synthesized. The truth is that the construction of urban infrastructure with non-permeable materials such as traditional concrete and asphalt significantly reduces rainwater flow to the soil layers and water table [7]. In a basin, the water cycle alteration can produce floods, river and lake disappearances, and consequently ecosystem extinction. Biological coatings for buildings such as green roofs and walls are used to mitigate urban threat and other environmental problems. In general, the benefits of green roofs and walls can be classified into three categories: environmental, economic, and social. Aspects such as thermal, moisture, noise, and electromagnetic protection in buildings, heat island effect reduction, sewage system load reduction, runoff water quality and air quality improvement, habitat development, and natural landscape reconstruction are among the major environmental benefits from green roofs and walls. From an economic viewpoint, green roofs and walls on buildings increase the property's commercial value, increase waterproof membrane lifespan, increase fire resistance, and reduce energy consumption. Regarding social aspects, these biological coatings improve the occupant's health and wellbeing, while they also help to generate employment for maintenance and even for food production at the urban scale (urban agriculture).

Recently, the use of green roofs on buildings increased significantly around the world due to different government incentives and due to pressure exerted by a new market that seeks products and processes that are more environmentally friendly. However, the lack of a detailed characterization and guidelines for their design resulted in the implementation of these biological coatings on buildings being currently based on experience, making them inefficient and even risky. In order to improve this situation, this review of the state of the art presents a proper green roof classification, which is based on their components. Similarly, a detailed description of the factors that control the hydraulic and thermal performance of green roofs is given. Based on these, an estimation of the impact of green roof systems in sustainable construction certifications is included. Finally, research challenges for the correct implementation of these biological coatings on buildings are addressed.

2. Components and Classification

2.1. Components

Although the green roof's most visible part is the vegetation layer, green roofs are multilayer systems in which each layer has different functions, impact on the complete life cycle (life-cycle analysis (LCA), and certifications for sustainable construction. This natural-based solution simulates the natural soil's characteristics, as presented in Figure 1. The multi-layer components of green roofs are described below.

(a) Vegetation layer: This can be composed of different biological species, usually plants or even trees. The respective species selection is based on availability, weather, maintenance conditions, and the substratum's depth, which depends on the structural building capacity [9]. Experience shows that green roof plants need to be chosen with care, as not all plants are suitable for growing in this way. For example, when choosing plants for a green roof, they need to be able to withstand wind and frost, be drought-resistant, tolerate living in poor soil, and require low maintenance. Also, green roof plants should also be attractive and offer food and shelter for wildlife. Although, many plants were proposed for green roofs in the literature, there is a need for comparisons among various types of plants to provide design guidelines for selecting the most appropriate vegetative layer for a given green roof [10]. Interesting research is now being conducted to analyze CO_2 reduction and O_2 production from different plant species; hence, this factor should also be included in the plant selection process for increasing the positive environmental impact of the biological coatings in life-cycle analysis.

(b) Substratum: The function of this layer is to physically support the vegetation and to supply the required nutrients for their development. Also, this layer should have the ability to store and gradually release excess rainwater, keeping enough moisture to later reduce maintenance activities. This layer is usually based on a combination of minerals with organic matter and other nutrients such as nitrogen, phosphorus, potassium, and magnesium [11,12]. Physical properties of a typical substratum are presented in Table 1.

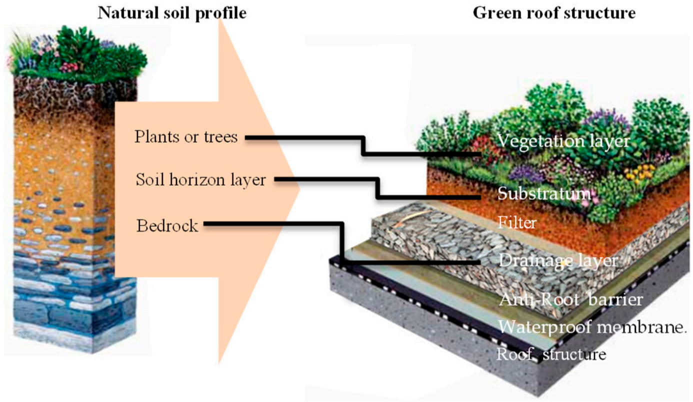


Figure 1. Green roof's basic components and their similarity with the natural soil. Modified from Ovacen (2014) [8].

Table 1. Physical properties of a typical substratum used in green roofs [13].

Physical Property	One-Layer System	Multi-Layered System
Water retention	Minimum 20%	Minimum 35%
Water permeability	Minimum 60 mm/min	Minimum 0.6 mm/min
Air content (fully saturated)	Minimum 10%	Minimum 10%
pH	6.5 to 9.5	6.5 to 8.0

(c) Filter: This building protective layer is usually a geotextile; its main function is to block the substratum's material flow to the drainage layer and to keep it in the right position. This geotextile, chemically neutral, has to be resistant to acid and alkaline attacks [3].

(d) Drainage layer: Also known as a drainage system, this layer is composed of granular-based material layers and pipelines. This is the key to appropriate vegetation growth and control of building water-associated problems such as filtrations. In particular, the drainage layer is responsible for the equilibrium between water excess and scarcity. It is normally formed by gravel, which is a natural crushed rock [14]. Research is now being conducted to reduce the use of natural aggregates to minimize the negative environmental impact of using nonrenewable resources in green roofs [15].

(e) Anti-root barrier: This high-density polyethylene layer protects the waterproof membrane from possible tearing caused by roots. It also functions as a second protection from the substratum to the building [3].

(f) Waterproof membrane: This layer is used to block the water flow to the building slab. Some of the most used waterproof membranes are thermo-polymer elastomers such as EPDM (ethylene propylene diene) or thermoplastic polyolefin (TPO), which are also good as root barriers [14].

2.2. Classification

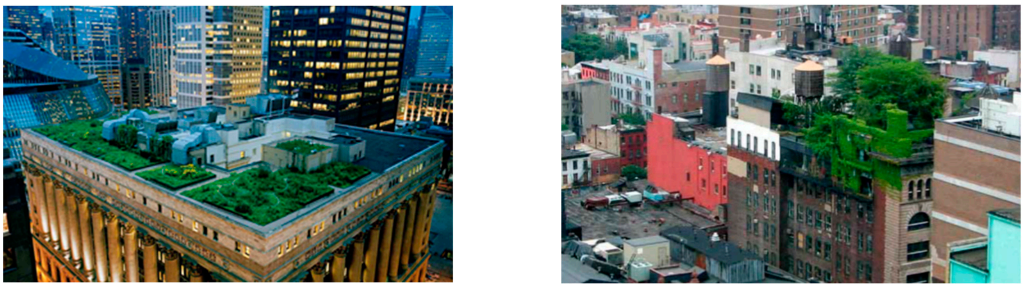
Although there are different criteria to classify green roofs, the most common classification at the international level is based on the characteristics of the vegetation layer, as presented below [16].

(a) Extensive: This green roof type uses plants with low-moisture needs (Figure 2). As a consequence, it uses a substratum with thickness between 5 and 15 cm. This biological coating is usually implemented on places with difficult access for pedestrians, can be moistened with rainwater, and can be placed on existing structures when the building has a proper design (i.e., roof live load considered as indicated in design codes). Its weight varies from 60 to 140 kg/m^2 [17].

(**a**) (**b**)

Figure 2. Extensive green roofs: (**a**) Icelandic house [18]; (**b**) Nanyang Technological University, Singapore [19].

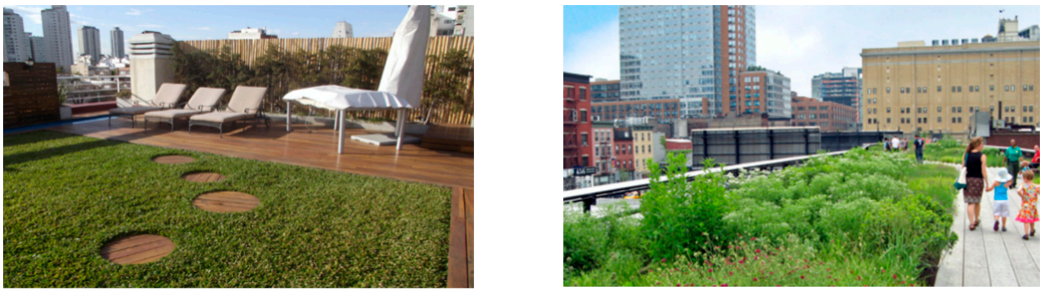
(b) Intensive: The green roofs belonging to this type have the possibility of using a great variety of plants and even tree species (Figure 3). Hence, they generally require substratum of great depth, usually superior to 15 cm. Based on the last aspect, these coatings can allow pedestrian access, require artificial water irrigation systems, and are placed on structures specifically designed to bear these additional loads. Their weight varies from 250 to 400 kg/m^2 [20].



(**a**) (**b**)

Figure 3. Intensive green roofs: (**a**) Chicago City Hall, Illinois [21]; (**b**) apartment building, New York [22].

(c) Semi-intensive: This type of green roof considers an intermediate system between intensive and extensive systems with species that grow over a 10 to 30-cm-deep substratum (Figure 4). It allows partial pedestrian access and requires artificial irrigation systems. Its weight varies from 60 to 140 kg/m^2 [23].



(**a**) (**b**)

Figure 4. Semi-intensive green roofs: (**a**) Buenos Aires, Argentina [24]; (**b**) High Line park building, New York [25].

3. Hydraulic Performance

Based on the non-permeable large areas generated by conventional urban development, green roofs might reduce the negative environmental impact, particularly by partially recovering the natural water cycle in a basin. These biological coatings on buildings have the ability to store water in the substratum, in which a fraction is absorbed by plants and returned to the atmosphere via evaporation and transpiration processes [26,27]. In addition to the efficient management of the evapotranspiration water fraction, another water fraction is absorbed, infiltrated, and stored inside the system layers. Depending on the precipitation intensity, substratum type, and depth, studies showed that green roofs have the capacity to store between 40% and 80% of annual precipitation that falls on them. Additionally, it was reported that a 12-cm layer takes 12 h to start releasing the stored water during a rain event, and it continues releasing it during the next 21 h, approximately [28]. Based on Kok et al. (2016) [29] and Masseroni and Cislagi (2016) [30], the discharge peak from a storm can be reduced by 26% to 35%. Hence, it is deduced that green roofs, in addition to reducing the magnitude of water volume captured by rain drainage systems, also delay the water discharge time, because the substratum and other layers require time to saturate and discharge the stored water, reducing potential flood impacts when used intensively at the urban scale [26]. In Germany, Spain, Holland, England, and the United States, the performance of different green roof types was evaluated toward the quantity and quality of urban runoff water. For example, van Woert et al. (2005) [14] indicated that the implementation of green roofs reduces the excess of runoff water, and Stovin (2009) [17] found 34% rainwater retention in the 11 precipitation events monitored. In this article, the retention capacity, measured as the water percentage stored in different green roofs compared with the water that passes through them, is presented in Table 2. From the results, it can be observed that retention capacities can range from 45% to 78% for different green roof systems. The variation in the results is associated with the substratum depth, initial water content, vegetation age and type, and precipitation intensity and distribution.

Table 2. Retention capacity from different green roof systems evaluated worldwide [31].

Rainwater Retention (%), Average during Study Period	Rainwater Retention (%), Range for Studied Events	Monitoring Time	Short Description and References Taken from Reference [31]
46	-	17 months	Bengtsson et al. (2005) [32] studied a hydrological function of a *Sedum* moss thin vegetated roof from Malmö, Sweden (roof slope 2.6%, substrate thickness 30 mm). The real rain events (mid July 2001 through December 2002) and artificial storms were investigated both on the study in real scale and on the smaller model of the green roof, designed identically to the original roof but with the possibility of changing the slope and the drainage material.
61	-	15 months	Van Woert et al. (2005) [14] investigated vegetated roof water retention and its dependence on roof surface type, slope, and media depth. Three roof platforms were constructed in a model scale with a slope of 2%: gravel, vegetated, and un-vegetated (study period: August 2002 through October 2003). Vegetated roofs consisted of the following layers: drainage (15 mm), water retention fabric (7.5 mm), additional retention fabric as vegetation carrier (7.5 mm), and 25 mm of growing media. Twelve additional roof platforms were used to examine roof slope (6 with slope 2% and 6 with slope 6.5%) and media depth (for 2% slope 25 mm and 40 mm; for 6% 40 mm and 60 mm).

Table 2. *Cont.*

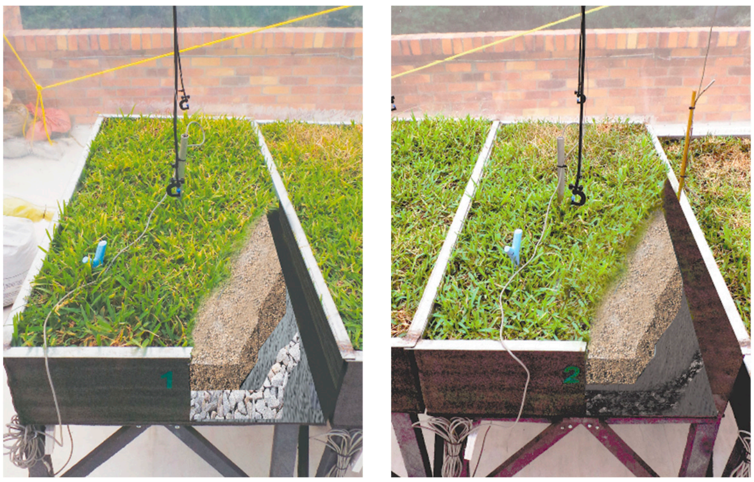
Rainwater Retention (%), Average during Study Period	Rainwater Retention (%), Range for Studied Events	Monitoring Time	Short Description and References Taken from Reference [31]
45	19–98	2 months	De Nardo et al. (2005) [33] investigated stormwater retention by three green roofs located in Pennsylvania, United States of America (USA). The roofs consisted of the following layers: waterproof membrane, drainage layer of 12 mm, growing medium 89 mm, plant support medium 25 mm. Rainfall and runoff data were collected for seven rain events during October–November 2002.
63—Roof 1	-	18 months	Moran et al. (2005) [34] monitored two green roofs installed in North Carolina, USA (in Goldsboro: soil depth 75 mm, flat, and in Raleigh: soil depth 100 mm, slope of 7%) to estimate water retention and peak flow reduction. Two different commercially available drainage systems were used: one in Goldsboro with negligible storage and one in Raleigh with water storage capacity of 2.4 L/m^2. The runoff data were collected at Goldsboro during April 2003–September 2004 and in Raleigh during July 2003–September 2004. To investigate water quality (P-tot, N-tot) runoff water samples were collected during 11 rain events from the Goldsboro green roof (soil mix consisting of 55% expanded slate, 30% sand, and 15% compost).
55—Roof 2	-	15 months	
78	39–100	13 months	Carter and Rasmussen (2006) [35] investigated water retention of a newly constructed green roof plot in Athens, Georgia, USA. The construction followed a design of a commercial product. In total, 31 rainfall–runoff events were registered during a study period of 13 months (November 2003–November 2004). The roof layers included a root protection sheet of negligible thickness, 4.8-mm-thick moisture retention mat with water retention capacity of 5 L/m^2, 38.1-mm-thick synthetic drainage panel with water retention capacity of 4 L/m^2 (both layers provided about 9-mm retention). The growing medium was 76.2 mm thick.
49	-	4 storm events	Monterusso et al. (2004) [36] performed a pilot investigation of water retention (calculated for individual rainfall events) and water quality of runoff among combinations of various commercial growing systems and vegetation types in Michigan, USA. Twelve roof platforms were installed, each divided into 3 parts with different vegetation. All platforms duplicated typical commercial green roof construction; 4 commercial drainage systems were installed. Platforms were set at a slope of 2%. The substrate depth was 100 mm for three types of drainage systems and 20 mm (*Sedum*) or 60 mm (natives) for the fourth drainage system. The soil mix consisted of 60% heat-expanded slate, 25% grade sand, 5% aged compost, and 10% peat. Three groups of vegetation were used, the first consisting of seven *Sedum* spp. propagated from seed, the second from two *Sedum* spp. planted from plugs, and the third consisting of 18 species of region (Michigan) native plants planted from plugs.

Table 2. *Cont.*

Rainwater Retention (%), Average during Study Period	Rainwater Retention (%), Range for Studied Events	Monitoring Time	Short Description and References Taken from Reference [31]
-	5–70	6 months	Bliss et al. (2009) [37] monitored a prototype green roof in Pittsburgh, Pennsylvania, USA. The 1150-m^2 extensive green roof consisted of a bitumen built-up membrane with root barrier, drainage, and filter fabric layer beneath 140-mm-thick synthetic growing medium made of expanded shale, perlite, and coconut husk. Regarding water quantity investigation, the data were obtained for 13 storms (August 2006–January 2007). Water quality tests (phosphorus, sulfate, nitrogen, chemical oxygen demand (COD) for unfiltered and filtered samples, pH and turbidity for unfiltered samples and lead, cadmium, and zinc for filtered samples) were reported for one of the two selected storms (17 October 2006 or 1 December 2006).

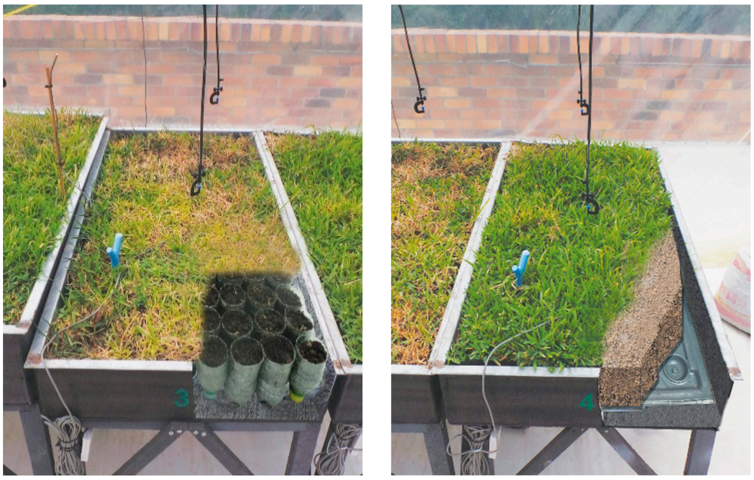
On the other hand, as mentioned previously for the drainage layer, recent research is evaluating new material sources to replace natural aggregates traditionally used on green roofs. In this case, drainage systems composed of PEAD plates (recycled high-density polyethylene), reused PET bottles (polyethylene terephthalate), and vulcanized recycled rubber particles were evaluated and compared with basal gravel, the conventional system used as a drainage system (Figure 5). The results indicated that, for low-intensity precipitations (simulations of 1 and 4 mm) and duration of a couple of hours, granular drainage systems (rubber and gravel) were very efficient, as they kept almost all precipitation water, and retention coefficients were about 100%. For the same conditions, reused PET bottles and PEAD plates retained half of the simulated precipitation, while retention coefficients were about 50%. For higher-intensity precipitations (simulations around 50 mm), the retention coefficients were near 30% for all green roof systems, except for the system composed of PET bottles, which had a retention capacity near to 0% [15].

Using the same experimental methodology but including a simulation for the Singapore precipitation regime, extensive green roofs of 12 cm were not enough to obtain a significant retention coefficient. The authors concluded that a proper green roof design has to be done for each precipitation condition [38]. Hence, more research has to be conducted to improve the retention coefficients in green roofs.



(**a**) (**b**)

Figure 5. *Cont.*



(**c**) (**d**)

Figure 5. Cross-transversal sections of green roof prototypes evaluated using reused and recycled materials as their drainage systems: (**a**) roof with basal gravel (reference); (**b**) roof with vulcanized recycled rubber particles; (**c**) roof with PET (polyethylene terephthalate) bottles; (**d**) roof with PEAD (recycled high-density polyethylene) plates [15].

4. Thermal Performance

In general, green roof systems produce a high thermal isolation effect in buildings by increasing thermal inertia. This interesting property is mainly due to the green roof components which work as thermal isolation chambers, preventing and delaying the temperature amplitudes due to their high thermal capacities in hot regions, as well as heat winter loss reduction in cold regions. Indeed, a green roof can reduce energy consumption from air conditioning in buildings to 50% [39]. In addition to the good thermal performance of green roofs, they also reduce the surrounding environment's temperature via vegetative physiological processes such as evapotranspiration, photosynthesis, and ability to store water [39]. Scale experiments in outdoor conditions on different green roof systems developed in Cali (Colombia) showed that, during days where the environmental temperature was high (over 35° C), there was a temperature reduction between 10.6 and 11.7 °C below the green roof prototypes [15]. These results are similar to those reported in the literature for tropical climates. More details about the prototype evaluation can be seen in Figure 6.

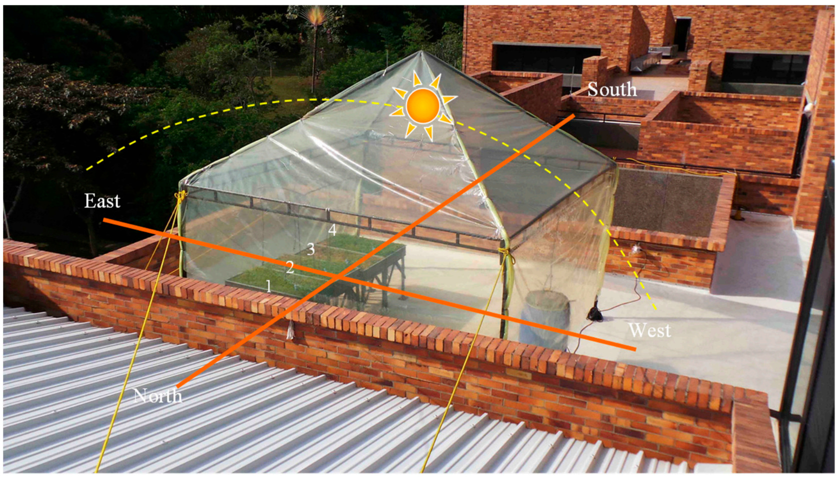


Figure 6. Green roof prototypes evaluated using reused and recycled materials in their drainage systems [15].

Table 3 summarizes results from several researchers about the thermal performance of different green roof systems. From these results, a trend to evaluate the thermal behavior of green roof systems during warm and cold seasons can be identified. Although some researchers showed a more efficient behavior in hot weather compared to cold weather, some others showed almost the same behavior. Based on the review, more research should be conducted when the substratum is in saturated conditions during cold weather; then, the isolating effect of green roofs seems to be significantly reduced [40].

Table 3. Relevant work related to the thermal performance of green roofs.

Approach Proposed	Major Findings	Reference
Long-term experimental analysis to compare thermal performance from a conventional roof respect to a green roof.	Under typical Mediterranean climate conditions, the green roof system provides different behavior according to the season. The green roof performance is meaningful during warm seasons, while this technology does not show a significant difference with a conventional roof during cold seasons.	[41]
Model based on energy balanced equations expressed for foliage soil media and simulations.	During the exposure to warm environmental conditions, the evapotranspiration provides evaporative cooling that increases the thermal resistance of a green roof system.	[42]
Analysis of transmittance and heat flux.	During the winter season, the green roof provides further isolation even in saturated conditions. In the summer, the green roof decreases incoming heat fluxes and ceiling temperatures.	[43]
Study during warm and cold periods with 3 different roof conditions.	During warm periods, the evaluated green roof reduced heat gain over 90%. During the cold period, the evaluated green roof system reduced heat loss between 70% and 84%. These results are comparable to those obtained with conventional ceramic and metallic roofs.	[44]
Numerical model and experimental validation for energy savings (comparison approach).	After evaluating extensive, semi-intensive, and intensive green roofs, the extensive one involved higher cooling energy demand than semi-intensive (2.8-fold) and intensive ones (5.9-fold).	[45]
Mathematical model and experimental validation.	Cooling potential of green roofs can be around 3.02 kWh per day for an LAI (leaf area index) of 4.5. This is enough to maintain an average room temperature of 25.7 °C.	[46]
Experimental study for measuring energy savings in cooling for Mediterranean continental climate.	Energy savings (16.7%) for cooling and an increase in energy consumption for heating (11.1%) were observed compared to conventional flat roofs. These results correspond to a 20% to >85% area covered by vegetation.	[47,48]

5. Certifications for Sustainable Construction

In order to evaluate the impact of green roof system implementation on major sustainable construction certifications, a preliminary qualitative impact analysis must be developed to assess the decision process. A suggested impact of the green roof system that varies from not related to high is presented in Tables 4 and 5, which summarize the impact of green roofs on the overall certification systems based on the degree of relevance of green roof benefits concerning the main criteria for each system. Thus, criteria regarding energy and water involve a strong (high impact) relationship (efficiency, cost reduction), while indoor and outdoor environment improvements involve indirect benefits (medium impact). Finally, innovation is considered as a less relevant criterion since its measurement in buildings is still subjective in terms of green roofs, and it can be interpreted as an indirect benefit or consequence.

Table 4. Suggested impact of green roof systems in sustainable construction certifications.

Impact	Description
High	In this level, a green roof has a direct influence on the evaluation criteria providing points in relation to conventional roofs. There is a strong relation to energy and water efficient use criteria.
Medium	Although, in this level, the implementation of green roof systems has an impact on the criteria, complementary technologies are required to be explicitly valued.
Low	At this level, the green roof implementation is related to the criteria, but it does not necessarily mean a performance improvement.
Not related	The implementation of green roof systems has no impact on the evaluation criteria in this level.

Table 5. Impact of green roof systems on different sustainable construction certifications.

BREEAM—Building Research Establishment Environmental Assessment Method	LEED—Leadership in Energy and Environment Design	CASBEE—Comprehensive Assessment System for Built Environment Efficiency	BEAM Plus—Building Environmental Assessment Method	ESGB—Evaluation Standard for Green Building
Management	Sustainable sites	Indoor environment	Site aspect	Sustainable site and outdoor environment
Health and wellbeing	Water efficiency	Quality of service	Material aspect	Energy use
Energy	Energy and atmosphere	Outdoor environment	Energy use	Water use
Transport	Material and resources	Energy resources and materials	Water use	Material use
Water	Indoor environmental quality	Off-site environment	Indoor environmental quality	Indoor environmental quality
Materials	Innovation in design		Innovation and performance enhance	Operation management
Waste	Regional priority			
Land use and ecology				
Pollution				
Innovation				

High impact: ; medium impact: ; low impact: ; not related: .

From the analysis of the impact of green roofs on construction certifications, it is clear that the British Accreditation, BREEAM (Building Research Establishment Environmental Assessment Method), considers the use of this technology more relevant. BREEAM assumes a high impact of green roofs in energy, water, pollution, land use, and ecology. Contrary to BREEAM, the Japanese Accreditation, CASBEE (Comprehensive Assessment System for Built Environment Efficiency), does not consider the use of green roofs crucial for sustainable construction. However, this accreditation system gives a reasonable importance to green roofs regarding energy resources and materials and in outdoor environments. On the other hand, LEED (Leadership in Energy and Environment Design), BEAM Plus (Building Environmental Assessment Method), and ESGB (Evaluation Standard for Green Building) give a medium impact of using green roofs in their accreditation systems.

In general, for the accreditation systems, green roofs are considered as a low-level innovation, unless they are integrated with other technologies such as renewable energies, cogeneration, and so on. That is due to the fact that green roof systems were implemented in many projects worldwide in the past. However, the real fact is that the impact of the implementation was never properly quantified for the hydraulic and thermal performances. Thus, other environmental benefits such as reduction of the heat island effect and sewage system load, improvement of runoff water and air quality, and reconstruction of natural landscapes remain to be estimated for each green roof case.

As a reference for the reader, a description of major construction certifications is included in Table 6.

Table 6. Description of major sustainable construction certifications based on Park et al. (2017) [49] and Lee (2013) [50].

Certification Systems	Characteristics	Measuring Method
BREEAM—Building Research Establishment Environmental Assessment Method	Most used certification used worldwide to measure, organize hierarchically, and certify a building's sustainability. More than 250,000 buildings in more than 70 countries have this certification. Origin: United Kingdom.	Hierarchical criteria credit system in the following categories: fulfilling, good, very good, excellent, and outstanding.
LEED—Leadership in Energy and Environment Design	This certification includes measuring and hierarchical organizing systems for design, construction, maintenance, and operation of green buildings that use some type of related technologies. More than 80,000 buildings worldwide have this certification. Origin: USA.	Certification system based on points as follows: platinum: more than 80 gold: between 60 and 79 silver: between 50 and 59 certified: between 40 and 49
CASBEE—Comprehensive Assessment System for Built Environment Efficiency	This certification system was designed to measure the impact on people's life quality, resource consumption, and environmental loads caused by buildings. This certification system is supported by the national government in Japan. Origin: Japan.	Valuation scale from 1 to 5. The minimal condition required by law is 3.
BEAM Plus—Hong Kong Building Environmental Assessment Method	This certification covers a wide variety of building impacts on local, global, and indoor scales. Origin: China.	The evaluation system has four levels: bronze: over 40% credits silver: over 55% credits gold: over 65% credits platinum: over 75% credits
ESGB—Evaluation Standard for Green Building	This certification was designed to evaluate new and existing buildings during the design and construction stages. Origin: China.	This certification has 3 levels: 1 start: over 33% marks 2 starts: over 67% marks 3 starts: over 80% marks

6. Conclusions and Research Challenges

Although green roofs were used in major ancient buildings, their implementation in modern infrastructure was restricted until Le Corbusier included them among the main building conceptual design points. However, green roofs became more a landscaping action rather than a technical solution with significant environmental, technical, economic, and social benefits. This is mainly due to the fact that there was no proper design, construction, and maintenance of these biological coatings. Intensive, semi-intensive, and extensive green roofs require a proper conceptualization that allows identification of each component and their functions for the overall performance.

Currently, the economic benefits from reducing building energy consumption and sewage system load attracted the attention of urban developers for implementing green roofs on buildings. This review showed that, only regarding the hydraulic performance, retention capacities vary from 45% to 78% for different green roof systems reported in the literature. Thus, more research has to be conducted to estimate the real impact of substratum depth, initial water content, vegetation age and type, and precipitation regime on the hydraulic performance. Similarly, although thermal gradients up to

10° were reported using green roofs in tropical climates, more research on the application of green roofs in cold climates has to be done. In this case, when the substratum is saturated, the isolating effect is significantly reduced. Therefore, combined models that integrate hydraulic and thermal performances should be developed. Thermal and hydraulic performances mostly control the complete green roof system.

Even though most accreditation systems for sustainable constructions do not give significant importance to green roof implementation, an accurate quantification of the environmental, technical, economic, and social benefits of green roofs might help to improve this situation, as well as address the lack of legislation for this technology in most countries.

Finally, from this review of the state of the art, research challenges that can be undertaken in the short or medium term toward an effective implementation of green roofs are presented in Table 7.

Table 7. Research challenges facing green roofs reported in the literature.

Component	Research Topics
Vegetation layer	(a) Study the vegetation behavior under different climate conditions. (b) Generate robust databases for plant analysis and its selection. Include CO_2 sequestration performance. (c) Study of influence of vegetation on green roof thermal and hydraulic performances. (d) Analyze the relationship and effect on wildlife.
Substratum	(a) Develop growth media mixtures able to reduce erosion and increase water content for low-depth substratum. (b) Develop growth media using renewable local materials.
Materials	(a) Improve root resistance from waterproof membrane and anti-root barrier. (b) Increase water retention capacity from the drainage layer materials. (c) Include reused, reduced, and recycled materials in all components of green roofs. (d) Durability strategies to increase life span.
Others	(a) Design and implementation of robust policies to promote massive use. (b) Evaluate green roof implementation using the life-cycle analysis (LCA) methodology. (c) Analyze the overall performance from a multidisciplinary perspective. (d) Develop local design and construction guidelines.

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References

1. Peri, G.; Traverso, M.; Finkbeiner, M.; Rizzo, G. The cost of green roofs disposal in a life cycle perspective: Covering the gap. *Energy* **2012**, *48*, 406–414. [CrossRef]
2. Williams, N.; Rayner, J.; Raynor, K. Green roofs for a wide brown land: Opportunities and barriers for rooftop greening in Australia. *Urban For. Urban Green.* **2010**, *9*, 245–251. [CrossRef]
3. Bliss, D.J. Stormwater Runoff Mitigation and Water Quality Improvements through the Use of a Green Roof in Pittsburgh, Pennsylvania. Master's Thesis, Faculty of the School of Engineering, University of Pittsburgh, Pittsburgh, PA, USA, 2010.
4. Getter, K.; Rowe, D. The role of extensive green roofs in sustainable development. *HortScience* **2006**, *41*, 1276–1285. [CrossRef]
5. Coutts, A.; Daly, E.; Beringer, J.; Tapper, N. Assessing practical measures to reduce urban heat: Green and cool roofs. *Build. Environ.* **2013**, *70*, 226–276. [CrossRef]

6. Eisenman, T. Raising the bar on green roof design. How does the ASLAs unconventional green roof perform? *Landsc. Archit.* **2006**, *2006*, 22–29.
7. González, Z. Agricultura. *Rev. Agropecu.* **1995**, *71*, 58–61.
8. Ovacen. Manuales o Guías Sobre Cubiertas Vegetales. Available online: http://ovacen.com/como-construir-cubiertas-vegetales-o-verdes-manuales-guias/ (accessed on 17 February 2014).
9. Oberndorfer, E.; Lundholm, J.; Bass, B.; Coffman, R.R.; Doshi, H.; Dunnett, N.; Gaffin, S.; Köhler, M.; Liu, K.K.; Rowe, B. Green roofs as urban ecosystems: Ecological Structures, Functions, and Services. *BioScience* **2007**, *57*, 823–833. [CrossRef]
10. Berardi, U.; GhaffarianHoseini, A.H.; GaffarianHoseini, A. State-of-the-art analysis of the environmental benefits of green roofs. *Appl. Energy* **2014**, *115*, 411–428. [CrossRef]
11. Villareal, E. Runoff detention effect of sedum green roof. *Hydrol. Res.* **2007**, *38*, 99–105. [CrossRef]
12. Wachtel, J. Storm water management, green roof style. *Biocycle* **2007**, *48*, 42–46.
13. Landscape Development and Landscaping Research Society–FLL. *Green Roof Guidelines-Guidelines for the Planning, Construction and Maintenance of Green Roofs*, 6th ed.; Landscape Development and Landscaping Research Society–FLL: Bonn, Germany, 2018.
14. Van Woert, N.D.; Rowe, D.B.; Andresen, J.A.; Rugh, C.L.; Fernández, R.T.; Xiao, L. Green roof stormwater retention: Effects of roof surface, slope, and media depth. *J. Environ. Qual.* **2005**, *34*, 1036–1044. [CrossRef] [PubMed]
15. Naranjo, A. Evaluación de Cubiertas Verdes Semi-Intensivas con Capas de Drenaje Elaboradas con Materiales Reciclados y Reutilizados. Master's Thesis, Pontificia Universidad Javeriana Cali, Cali, Colombia, 2017.
16. University of Cincinnati. Classification system proposed for green roofs. *ScienceDaily*. Available online: www.sciencedaily.com/releases/2013/10/131022113547.htm (accessed on 12 January 2020).
17. Stovin, V.; Duannet, N.; Hallam, A. Green Roof. Getting sustainable drainage off the ground. In Proceedings of the 6th International Conference of Sustainable Techniques and Strategies in Urban Water Mangement, Lyon, France, 25–28 June 2007; pp. 11–18.
18. Ecofield. Tejados de Cesped. Available online: http://ecofield.com.ar/blog/tejados-de-csped-y-muros-de-paja/ (accessed on 20 February 2018).
19. ArchiExpo. A Swirling Green Roof Tops the Gorgeous Nanyang Technical University in Singapore. Available online: https://projects.archiexpo.com/project-23031.html (accessed on 20 March 2015).
20. López, C. Un acercamiento a las Cubiertas Verdes. *Medellín FBPSA* **2010**, *2010*, 22–23.
21. Youtech & Associates. Urban Matter. Chicago City Hall. Available online: http://urbanmatter.com/chicago/chicago-city-hall/ (accessed on 10 May 2016).
22. EcoInventos. Azotea verde en Manhattan. Available online: http://ecoinventos.com/azotea-verde-en-manhattan/ (accessed on 11 April 2011).
23. García, I. Beneficios de Los Sistemas de Naturación en Las Edificaciones. In Proceedings of the XXXIV Semana Nacional de Energía Solar, Guanajuato, Mexico, 4–9 October 2010; pp. 1–5.
24. MAyEP/GCBA. Buenos Aires Ciudad. Techos verdes. [Figura]. Obtenido de. Available online: http://www.buenosaires.gob.ar/noticias/techos-verdes-en-buenos-aires (accessed on 13 April 2010).
25. Zinco. Referencias Cubiertas Ajardinadas. 2011. Available online: http://www.zinco-greenroof.com.ar/referencias/internacional/cubierta_jardin.html (accessed on 12 October 2011).
26. Carter, T.; Keeler, A. Life-cycle cost-benefit analysis of extensive vegetated roof systems. *J. Environ. Manag.* **2008**, *87*, 350–363. [CrossRef] [PubMed]
27. Wong, N.H.; Cheong, D.; Yan, H.; Soh, J.; Ong, C.L.; Sia, A. The effect of rooftop garden on energy consumption of a commercial building in Singapore. *Energy Build.* **2003**, *35*, 353–364. [CrossRef]
28. Scholz-Barth, K.; Tanner, S. *Federal Technology Alert: Green Roofs. Energy Efficiency and Renewable Energy (EERE). U.S.*; Energy Efficiency and Renewable Energy: Washington, DC, USA, 2004.
29. Kok, K.H.; Mohd Sidek, L.; Chow, M.F.; Zainal Abidin, M.R.; Basri, H.; Hayder, G. Evaluation of green roof performances for urban stormwater quantity and quality controls. *Int. J. River Basin Manag.* **2016**, *14*, 1–7. [CrossRef]
30. Masseroni, D.; Cislaghi, A. Green roof benefits for reducing flood risk at the catchment scale. *Environ. Earth Sci.* **2016**, *75*, 1–11. [CrossRef]
31. Czemiel Berndtsson, J. Green roof performance towards management of runoff water quantity and quality: A review. *Ecol. Eng.* **2010**, *36*, 351–360. [CrossRef]

32. Bengtsson, L.; Grahn, L.; Olsson, J. Hydrological function of a thin extensive green roof in southern Sweden. *Nord. Hydrol.* **2005**, *36*, 259–268. [CrossRef]
33. DeNardo, J.C.; Jarrett, A.R.; Manbeck, H.B.; Beattie, D.J.; Berghage, R.D. Stormwater mitigation and surface temperature reduction by green roofs. *Trans. ASAE* **2005**, *48*, 1491–1496. [CrossRef]
34. Moran, A.; Hunt, B.; Smith, J. Hydrological and water quality performance from green roofs in Goldsboro and Raleigh, North Carolina. In Proceedings of the Green Roofs for Healthy Cities Conference, Washington, DC, USA, 4–6 May 2005.
35. Carter, T.L.; Rasmussen, T.C. Hydrologic behavior of vegetated roofs. *J. Am. Water Resour. Assoc.* **2006**, *42*, 1261–1274. [CrossRef]
36. Monterusso, M.A.; Rowe, D.B.; Rugh, C.L.; Russell, D.K. Runoff water quantity and quality from green roof systems. *Acta Hortic.* **2004**, *639*, 369–376. [CrossRef]
37. Bliss, D.J.; Neufeld, R.D.; Ries, R.J. Storm water runoff mitigation using a green roof. *Environ. Eng. Sci.* **2009**, *26*, 407–417. [CrossRef]
38. Van Spengen, J. The Effect of Large-Scale Green Roof Implementation on the Rainfall-Runoff in a Tropical Urbanized Subcatchment: A Singapore Case Study. Master's Thesis, Faculty of Civil Engineering and Geosciences, TUDelft, Dordrecht, The Netherlands, 2010.
39. Minke, G. *Techos Verdes Planificación, Ejecución, Consejos Prácticos*; Editorial Fin de siglo: Montevideo, Uruguay, 2004.
40. Collins, S.; Kuoppamäki, K.; Kotze, D.J.; Xiaoshu, L. Thermal behavior of green roofs under Nordic winter conditions. *Build. Environ.* **2017**, *122*, 206–214. [CrossRef]
41. Theodosiou, T.; Aravantinos, D.; Tsikaloudaki, K. Thermal behaviour of a green vs. a conventional roof under Mediterranean climate conditions. *Int. J. Sustain. Energy* **2014**, *33*, 227–241. [CrossRef]
42. Ouldboukhitine, S.-E.; Belarbi, R.; Djedjig, R. Characterization of green roof components: Measurements of thermal and hydrological properties. *Build. Environ.* **2012**, *56*, 78–85. [CrossRef]
43. D'Orazio, M.; Di Perna, C.; Di Giuseppe, E. Green roof yearly performance: A case study in a highly insulated building under temperate climate. *Energy Build.* **2012**, *55*, 439–451. [CrossRef]
44. Parizzotto, S.; Lamberts, R. Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianopolis city, Southern Brazil. *Energy Build.* **2011**, *43*, 1717–1722. [CrossRef]
45. Silva, C.M.; Gomes, M.G.; Silva, M. Green roofs energy performance in Mediterranean climate. *Energy Build.* **2016**, *116*, 318–325. [CrossRef]
46. Kumar, R.; Kaushik, S.C. Performance evaluation of green roof and shading for thermal protection of buildings. *Build. Environ.* **2005**, *40*, 1505–1511. [CrossRef]
47. Pérez, G.; Vila, A.; Rincón, L.; Solé, C.; Cabeza, L.F. Use of rubber crumbs as drainage layer in green roofs as potential energy improvement material. *Appl. Energy* **2012**, *97*, 347–354. [CrossRef]
48. Coma, J.; Pérez, G.; Solé, C.; Castell, A.; Cabeza, L.F. Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renew. Energy* **2016**, *85*, 1106–1115. [CrossRef]
49. Park, J.; Yoon, J.; Kim, K.-H. Critical Review of the Material Criteria of Building Sustainability Assessment Tools. *Sustainability* **2017**, *9*, 186. [CrossRef]
50. Lee, W. A comprehensive review of metrics for building environmental assessment schemes. *Energy Build.* **2013**, *62*, 403–413. [CrossRef]