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Review

Hydroponic Green Roof Systems as an Alternative to Traditional Pond and Green Roofs: A Literature Review

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Abstract: Among the several methods investigated over the past few years for the thermal mitigation of buildings in urban areas, green roof systems seem to be one of the most suitable solutions for several reasons, and researchers encourage the further study and implementation of these roofing techniques because of the potential benefits that they offer. So far, intensive, extensive and semi-intensive green roofs are considered to be a better option in terms of both energy efficiency and green area increase. However, there are some aspects that cause green roofs not to be suitable to every application, preventing their use from spreading, such as high maintenance and costs required by these sophisticated systems. Few studies aimed at overcoming the limits of green roofs have hinted at the possibility of implementing hydroponic cultures in green roof systems. This soil-less technology might overcome some issues, such as identifying the suitable substrate to support the growth of the vegetation. This paper aims to provide a systematic review of hydroponic green roof systems (HGRS), based on the rigorous analysis of the evidence gathered from the thorough evaluation of the available literature on the subject, in order to assess their potential use as an alternative to traditional green roofs. The review was carried out by analyzing studies that have assessed the performance of hydroponic green roofs as well as those of comparable systems, such as pond roofs and green roofs. The results of these studies show that HGRS provide similar performances to the above-mentioned systems in terms of the passive conditioning effect, lowering the cooling/heating load of buildings, with slight changes depending on the climatic conditions. However, they offer other significant properties such as higher efficiency in water runoff management, alongside others discussed in this paper, while also requiring minor maintenance. Significant results have been provided; however, gaps in the knowledge have also emerged, and further studies need to be conducted to provide exhaustive information.

Keywords: green rooftops; thermal mitigation; environmental footprint; passive cooling/heating; indoor comfort; urban greening

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1. Introduction

Buildings are one of the main sources of environmental impact, as they are responsible for huge amounts of gas emission and represent a significative percentage of the total annual energy consumption, due to the resources needed for heating, cooling and ventilation. Over the last few decades, studies have focused on implementing innovative building components that can help in reducing carbon emissions and optimizing the use of energy necessary for all building activities, which represents a severe issue all over the world. In Europe, buildings represent 40% of the total energy consumption and 36% of the overall CO_2 emissions [1,2].

A large amount of energy used by buildings is that demanded for cooling during the hot season. With the aim of reducing the indoor temperature of buildings but at the same time limiting cooling loads in order to pursue a lower environmental impact, researchers have focused on how to achieve this goal through construction techniques and innovative building envelopes.

Amongst the several methods investigated over the past few years for the thermal mitigation of buildings in urban areas, green roof systems seem to be one of the most suitable solutions for several reasons: air temperature reduction, shield solar radiation shielding during hot seasons, water runoff management, and urban heat island effect mitigation.

Furthermore, studies show that vegetation on the ground and on roofs mitigates summer temperatures, decreases the indoor cooling load demand, and improves outdoor comfort [3]. Researchers encourage the further study and implementation of these roofing techniques [4–7] because of the potential benefits that they offer.

Despite the fact that the market for green roofs has been growing, there are some drawbacks, which represent part of the reason why the use of these systems has not spread further worldwide. Some of these have to do with the substrate layer, which represents the plants' growing media and therefore has great importance for the success of the green roof. Several materials can be used to build the substrate layer, which needs specific physical and chemical characteristics in order to perform well.

The substrate needs to contain a series of components mixed together in specific ratios: it must have the necessary nutrients for plant growth but at the same time it must not contain an excessive amount of organic component in order not to promote the growth of weeds. In fact, studies on this matter [8–10] show that adding organic material improves the physical properties necessary for the growth and maintenance of vegetation; however, the same organic material often represents a potential source of contamination for the water runoff of the roof, mainly due to the lack of stability of organic matter.

For this reason, many companies that sell green roof components have designed substrates tailored to the specific applications and to the local material availability. However, in countries where commercial substrates are not available, users often use common garden soil, which unfortunately has a number of disadvantages, such as low water retention, weight (agricultural soil with a thickness of 50 cm can reach a wet weight of 800–900 kg/m^2, which cannot be supported by a normal slab), and the presence of weeds.

It is partially for these reasons that in recent years, the idea of implementing soil-less crop techniques or hydroponic cultures into roofing systems has arisen.

Studies on green roof systems [7–11] have shown how the construction of green roofs is more challenging regarding system installation, maintenance, and weed and root control than hydroponic systems [12].

In order to achieve the best growth regulation and development of greenery, the design of soil-less systems for plant growth is a more efficient solution, in terms of the rationalization of water consumption and chemical elements for the fertigation of plants [13–15]. In fact, incorrect irrigation or fertilization can cause water or nutritional stress, requiring extra operations to restore the substrate to correct humidity and the plant system to optimal growth.

Soil-less cultivation takes place mainly thanks to a nutrient solution dissolved in water. Unlike traditional cultures, in hydroponic systems, the nutrient solution provides the plant with the substances it needs for its biological development.

Studies about hydroponic rooftop systems [8,12,16–21] are relatively new; most of them have been conducted in Asian and Middle Eastern countries, while others were conducted in European countries, such as Spain and Portugal for the most part, while a small percentage of them have been conducted in other countries such as Greece and Germany, and few of them have been carried out in the United States (Figure 1).

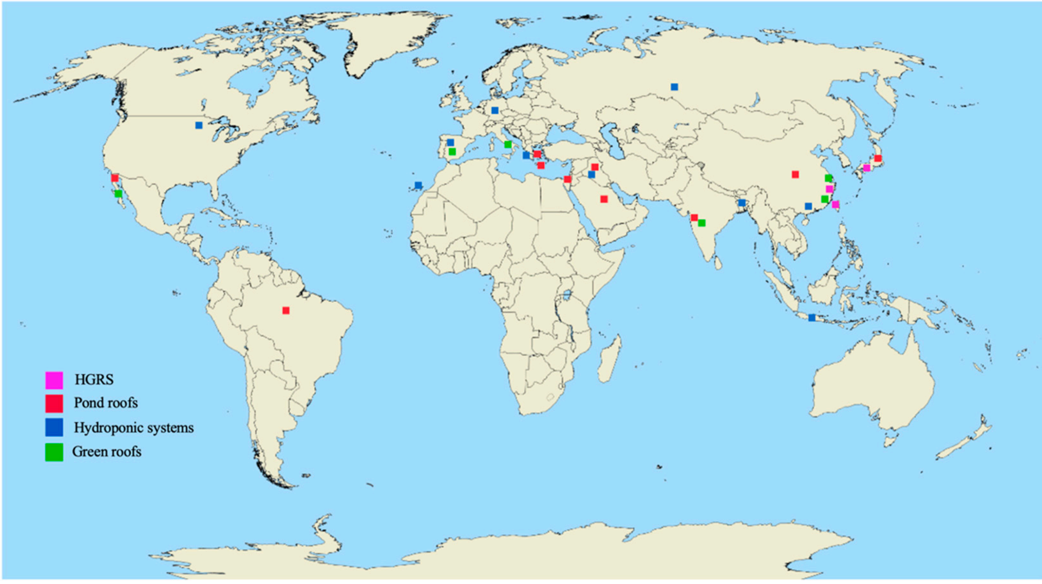


Figure 1. Geographic individuation of analyzed studies on hydroponic green roof systems [12,18–20], pond roofs [6,22–27], hydroponic systems [17,28–31], green roofs [4–6,8,23,32].

Hydroponic cultivations have mostly been studied not only because they are a sustainable alternative to traditional agriculture in terms of water and soil consumption [13], but also because these soil-less systems can be implemented in urban areas, providing benefits such as an increase in crop production for the population, a reduction in food transportation and waste and the improvement of food safety [16] thanks to a production policy based on “controlled environment agriculture” [17]. In addition to these, researchers have investigated how implementing building-integrated agriculture (BIA) [33] can contribute to optimizing their energy and resource consumption through the trade-off between the building and the cultivation system; for example, the latter can enhance building insulation while also using recycled waste produced by the users inside the building for its operation, from the perspective of life cycle assessment (LCA). Just as iRTGs (integrated rooftop greenhouses) can reuse the CO_2-dense airflow produced by the users inside the building to help plant growth [33], HGRS can potentially reuse building wastewater.

In terms of building energy efficiency, as the layers of extensive green roofs dampen solar radiation providing a cooling effect on the roof, therefore improving the indoor comfort [4], the water in the hydroponic system can provide the same “buffer” effect to the roof, contributing to lowering the envelope temperature and subsequently the indoor air temperature. The passive cooling of the building promotes a cooling load decrease, i.e., less energy is required to mechanically manage indoor air temperature [34].

Studies conducted on the energy efficiency of buildings’ envelopes, through green and pond systems, have mostly focused on reducing the cooling load during the hot season; however, a few researchers have touched on how it is also possible to effectively reduce heating load during winter as well [32,35–37].

The following review aims to provide an input to the research in the field of environmental impact mitigation through innovative building technologies, showing that HGRS have the potential to provide benefits regarding several environmental components, managing to offer higher overall performance than those of established and better-known practices. For this reason, further studies on this subject are encouraged.

In order to organize the data gathered from the analyzed studies, the paper is structured in eight sections as follows:

Section 2 describes the approach used to carry out the study, based on the information available on the tackled topic. Section 3 provides an overview of the hydroponic cultivation systems available and how each of them works, with the aim of describing how they can be implemented as green roof techniques. Sections 4–7 present the studies conducted on thermal performance, water management and the rooftop farming potential of hydroponic systems, the main results obtained and the comparison with the more developed green roofs and pond roofs, both in terms of energy and environmental benefits. Section 8 provides a discussion of the main results gathered from the literature and the knowledge gap in the current state of the art.

2. Materials and Methods

This study consisted of a systematic review carried out in order to lay out the information gathered so far on the matter of hydroponic green roof systems. Studies available on this topic are very limited, since these systems have only recently been investigated as an alternative to extensive green roofs. In fact, hydroponic systems as a cultivation method are fairly recent themselves.

The data provided by the current literature in regard to hydroponic green roofs are fragmented, since the few articles available each focus on a different aspect.

Therefore, this review paper aimed to provide a holistic view on the topic of hydroponic green roofs, tapping into the various aspects that can make these systems competitive in the field of sustainable building technologies.

The main issues tackled by this review paper were the effectiveness of hydroponic green roof systems in determining roof surface temperature decrease and therefore providing passive cooling, while also contrasting the performances of similar hydroponic roof configurations in different geographic areas. Additionally, the environmental benefits of such systems were considered, in terms of water and air quality and urban agriculture potential, in order to make a comparison with other proposed practices developed to mitigate the negative effects of urbanization, such as traditional green roofs, pond roofs and rooftop greenhouses.

The analyzed literature included peer-review journal articles, research articles, conferences and book chapters. Overall, over seventy studies were analyzed for the purpose of this review; twelve of them were left out, not being considered relevant to the study. Amongst the reviewed articles, however, only a small percentage were strictly on HGRS, due to a limited number of studies having been conducted on this subject (four articles specifically analyzing HGRS thermal and hydrological performance were found). The other studies included in this review examine environmental and energy performance of green roofs and pond roofs, whose operational principles are comparable as mentioned, with a few of them performing a comparison of their performance. Articles pertaining to urban agriculture were included, while papers that deal strictly with cultivation techniques for hydroponic crops were left out of the study sample.

The information gathered in this review was provided by articles regarding different aspects of hydroponic green roofs as well as a few background studies on the operation of hydroponic cultures.

The electronic databases ScienceDirect (http://www.sciencedirect.com) [38] and Scopus (http://www.scopus.com) [39] were used to gather the reviewed articles, using the keywords: "hydroponic", "soil-les", "hydroponic green roof systems", "roof ponds", "green roofs", "rooftop greenhouses", "passive cooling", "passive heating", "evaporative cooling". Table 1 provides a summary of the studies providing the most significant information and shows the main indicators considered when analyzing the existing literature.

Table 1. Summary scheme of analyzed studies.

Ref.	Country	Investigated System	Type of Study	Topic	Climate	Time Period	Methodology
Dong et al. [4]	Xiamen Island, China	Green roofs	Case study	Cooling effect of green roofs in high-density urban areas	-	2015 2017	Quantitative assessment of green roofs' cooling effect at the urban scale through LST comparison
Paithankar and Taji [5]	Maharashtra State, India	Green roofs	Model	Hydrological performance of green roofs (storm water management model)	Subtropical	Rainfall data from 2005 to 2015	Simulation through Storm Water Management Model (SWMM)
Berardi et al. [6]	California, USA	Green roofs pond roofs	Experimental	Indoor thermal comfort enhancement through water-to-air heat exchangers and indirect evaporative and radiant cooling	hot and dry	August 2015–September 2016	In situ measurement of thermal characteristic of two test cells with a green roof coupled with a WAHE for assessing cooling performance in the nighttime
Huang et al. [12]	Taichung, Taiwan	HGRS [1]	Experimental	Rooftop temperature and heat amplitude reduction effect of hydroponic green roofs	Subtropical	27 July–15 September 2014	Measurement of hydroponic roofs' (1) thermal performance, at different depths of water and (2) thermal performance with and without vegetation. Comparison of thermal performance of hydroponic green roofs and extensive green roofs
Goodman et al. [17]	NYC, USA	Hydroponics CEA [3]	Case study	Vertical and soil-less systems for controlled environment agriculture	-	2016	Data collection on the state of CEA and critical analysis to assess the environmental, economic and social potential of projects located on publicly owned rooftops and land

Table 1. *Cont.*

Ref.	Country	Investigated System	Type of Study	Topic	Climate	Time Period	Methodology
Tanaka et al. [18]	Osaka, Japan	HGRS [1]	Experimental Modelling	Rooftop heating mitigation during summer	Warm and temperate	1 July–31 August 2013	Observation of air temperature, rooftop surface temperature, and conductive heat flux; calculation of three thermal mitigation indices; definition of normalized types of mitigation indices
Tanaka et al. [19]	Osaka-Kyoto, Japan	HGRS [1]	Experimental Modelling	Rooftop heating mitigation during summer	Warm and temperate	1 July–31 August 2013 1 July–31 August 2014	Observation of air temperature, rooftop surface temperature, and conductive heat flux; heat balance assessment through net radiation and latent heat flux equations
Xu et al. [20]	Wenzhou, China	HGRS [1]	Experimental	Performance of hydroponic green roof systems in rainwater and greywater management	Warm and temperate	September 2017–August 2018	In situ collection of rainwater samples and synthetic greywater treatment; observation of changes in water concentration
Almodovar and La Roche [22]	Pomona (CA)	Pond roofs	Experimental	Cooling performance of a pond roof combined with a WAHE system	hot and dry with mild winters	August–October 2016	In situ measurements of surface and air temperature; definition of predictive equations to effectively dimension the WAHE system
Alexandri and jones [23]	Athens, Mumbai, Riyadh	Green roofs pond roofs pergolas	Experimental	Cooling techniques for urban spaces	hot and dry hot and humid hot and arid	July May July	Measurement of air and surface temperature
Pearlmutter and Berliner [25]	Negev Highlands, Israel	Pond roofs	Experimental	Pond roof variants to enhance their cooling performance	hot and arid	August 2013	Observation of a psychrometric roof pond (PRP), using an elevated lightweight shading structure to eliminate radiant heat loads at daytime and allowing free air flow to maximize evaporation

Table 1. *Cont.*

Ref.	Country	Investigated System	Type of Study	Topic	Climate	Time Period	Methodology
Krüger et al. [26]	Brazil	Pond roofs	Experimental	Cooling performance of an indirect evaporative cooling system (IECS)	subtropical	October 2014–January 2016	In situ assessment of the thermal performance of an IECS on experimental test cells
Su et al. [29]	Guangzhou, China	Hydroponics UA [2]	Experimental	Increase in crop production in hydroponic based rooftop farming	Subtropical	2018	Production tests of 10 leafy vegetables, using a low-cost reflector-assisted two-layer hydroponic system
Jiménez-Arias et al. [30]	Canary Islands, Spain	Hydroponics, soil-less	Experimental	Recycling of rejected brine (RB) from desalination for hydroponic culture	-	-	Chemical analysis for comparing the tested RB with a standard solution for hydroponic culture; crop yield and commercial quality analysis
Gagliano et al. [32]	Catania, Italy	Green roofs	Experimental Modelling	Thermal behavior of extensive green roofs	Mediterranean with dry summer and mild winter	27 July–24 August 2015	Measurement of outdoor surface temperature of the green roof and dynamic simulation for a numerical model

[1] Hydroponic green roof systems; [2] urban agriculture; [3] controlled environment agriculture.

3. Principles of Using Hydroponic Green Roofs as Cooling Systems

HGRS can be considered a combination of extensive green roofs and pond roofs. Therefore, the implementation of such roofing techniques potentially provides a series of benefits deriving from both of the aforementioned systems, ranging from environmental impacts, i.e., air quality improvement, water runoff management, urban heat island (UHI) effect reduction [3,4,12,13,16,17,33,34,40,41], to passive conditioning through cooling for indoor temperature management [22].

Many hydroponic techniques have been developed for soil-less cultivations [42]; however, some techniques are more suitable than others to be implemented as green roof techniques due to their characteristics.

Hydroponic Systems

The six existing types of hydroponic systems differ from one another mainly based on the method used to provide the nutrient solution to the plants. The most widespread technique is the nutrient film technique (NFT) [42,43], consisting of a system of channels, generally PVC pipes, in which a constant flow of nutrient solution is maintained (Figure 2a). The system requires hydroculture pots filled with expanded clay with holes in the bottom to let the roots pass through, a collection tank where the pots can be arranged with seedlings or sprouts, a nutrient film placed at the bottom of the tank, a tank for collecting water and a pump that allows the movement of the liquid and the nourishment of the plants: the system is set so that the irrigation water carries the nutrients from the bottom of the container to the roots of the plants and then returns to the tank from which it started.

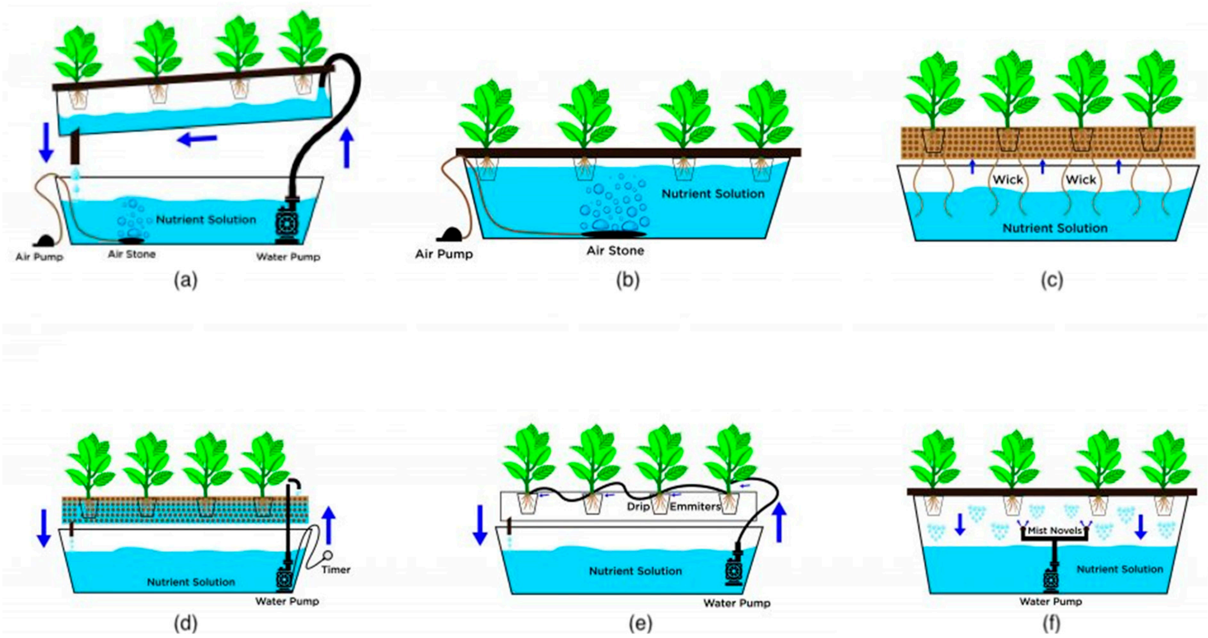


Figure 2. Different hydroponic system techniques: nutrient film technique (NFT) (**a**); deep water culture (DWC) (**b**); wick system (**c**); ebb and flood system (**d**); drip system (**e**); aeroponic system (**f**). Adapted from [44].

The other most popular hydroponic cultivation system is deep water culture (DWC) [14,42,43]. In this case, the plants float above a water tray thanks to a polystyrene or Styrofoam board structure, with the roots soaked in an oxygenated solution, consisting of water and nutrients (Figure 2b). The plants are placed inside plastic perforated containers, with the roots hanging out and then holes are drilled into the board, which can be set either on the edges of the tray or directly floating on the water.

Methods such as the wick system (Figure 2c) and the ebb and flood system (Figure 2d) [42] are similar to the deep water culture system but with some differences: the first consists of a self-feeding technique in which plants draw the nutrient solution directly from the reservoir through a wick by capillarity, which is only suitable for smaller plants, since the wick can only supply a small amount of water; while in the second, the plant roots are also placed into the tank but are cyclically flooded and drained, which means the amount of water in the tank is not constant.

Other methods, such as drip system (Figure 2e) and aeroponics (Figure 2f) [42], work by spraying or nebulizing the solution onto the plants, involving a smaller amount of water, even though they still require a reservoir for the water/nutrient solution regardless how it is delivered to the plants.

According to the said characteristics, deep water culture technique seems to be most suitable for application as a green roofing system when insulation benefits are pursued alongside the environmental and aesthetic benefits of greenery: the water tray in which the plant roots are submerged acts as an insulating layer for the building.

Nonetheless, while, as mentioned in most hydroponic cultivation systems, the roots are periodically sprayed and are in contact with water only at certain times of the day, the water depth in the DWC tank provides greater stability of the nutrient solution, which translates into less maintenance.

As for the vegetation, many types of plants can be selected as the "green layer" of the roof, from several vegetable specimens to ornamental plants; the majority of local plants can be grown with hydroponic systems, while common vegetables such as lettuce, cabbage and broccoli are durable specimens that can be grown in any climatic condition [45].

4. Passive Cooling Designs

A large percentage of studies on building design focus on developing energy-efficient building envelopes able to achieve indoor comfort with passive technologies, i.e., with little to no need for additional energy required for tasks such as cooling and heating, which are proven to be the most energy demanding operations [22,23,34]. This applies to all types of buildings (residential, commercial, educational, etc.), especially those where indoor comfort affects living quality and productivity [36,46–50].

One of the most compelling issues is buildings overheating during summer, especially in hot regions.

A viable option for passive cooling design is the implementation of HGRS. These systems take advantage of the heat exchange between the roof and the environment. The roofs' surface is cooled down by evaporation and/or longwave radiation to the sky: in fact, the water element absorbs and dissipates the incoming heat, acting as a pond roof. In the same way, during the cold season, the water stores the heat from solar radiation during the day and then releases it at night, transferring it to the building below mainly by convection [21,22,25,35,41,51].

In the past few decades, environmental phenomena such as the UHI effect [52] have encouraged these studies to focus on solutions at the urban scale as well as the building scale.

4.1. Passive Cooling Performance of Hydroponic Green Roof Systems (HGRS)

Aside from the common benefits that promote the use of hydroponic systems, such as being an easy method to increase green spaces and produce crops in urban areas, hydroponic-based green roofs have the potential to compete with traditional vegetate roofs under the energetic aspect. Studies carried out on this matter are still very limited; however, the few that are present in the literature show HGRS's potential to be a valid option amongst energy-efficient technologies.

Most studies focus on the investigation of HGRS designs, based on experimental assessment of thermo-physical performance, and their comparison with widely known practices such as green roofs and pond roofs. As with the latter, researchers consider them to be particularly effective in reducing cooling loads during warmer seasons.

Therefore, significant results have been gathered from studies performed in highly urbanized cities in areas with hotter climates.

Huang et al. [12] carried out a study comparing the effects of hydroponic green roofs and extensive green roofs on the reduction in rooftop temperature and heat amplitude in the subtropical climate condition of Taichung, the third largest city in Taiwan.

They investigated the temperature reduction of a hydroponic roof with water at three depths, first testing the trays only with water and no vegetation, and afterwards with the addition of two different plant species. The experiment was conducted in three stages: (1) measurements of the hydroponic roof at three depths of water, 10, 20 and 30 cm; (2) comparison of the hydroponic roofs' thermal performance with and without vegetation; (3) comparison between the hydroponic roof design and an extensive green roof with the same vegetation.

The experimental setup was built using three 50 × 50 × 30 cm hydroponic tanks at the three aforementioned water depths, and it was located on the uncovered rooftop of a three-story building, constructed from a concrete slab covered with ceramic tiles. The field measurements were carried out from 27 July 2014 to 15 September 2014, which are the hottest months in Taichung.

Temperature sensors were placed underneath each tank, at the center, and on the bare roof (simulated by laying 50 × 50 cm cement boards on top of the ceramic tiles) as well, collecting temperature data at 10 min intervals.

The surface temperature sensors monitored the mean, maximum and minimum rooftop temperature, while the mean, maximum and minimum air temperature and climatic parameters of RH and solar radiation were registered by a weather station placed in the tank's proximity, at a height of 1.50 m above the rooftop surface.

With these data, the surface temperature reduction was assessed by calculating the ΔT between the temperature of the control roof (simulated bare roof) and the slab temperature measured underneath the tanks.

The results show that, due to the evaporation and thermal insulation provided by the water, the 10 cm-deep hydroponic roof determined an average temperature decrease of 11 °C and a heat amplitude decrease of 60.6%. Both 20 and 30 cm water depths can determine a similar temperature reduction and a heat amplitude decrease of 63.5%. Therefore, the 10 cm-deep hydroponic roof was considered as the most efficient, because the performance increase at higher depths is marginal in comparison to the load increase.

From measurements conducted over a single day (4 August 2014) from 6 a.m. to 6 p.m., it was observed that the surface temperatures curves of the hydroponic roofs at 10, 20 and 30 cm almost overlap each other, indicating that no significant differences in measurements were detected at different water depths.

As far as the vegetation presence is concerned, it was observed that the addition of the plants determined a further reduction in the roof temperature in the range of 3 to 5 °C [12], without noticeable differences between the two types of vegetation, showing that, as can be expected, the cooling effect of the system is enhanced thanks to evapotranspiration determined by plants [53,54]. In fact, compared to water evaporation, evapotranspiration by plants releases more heat and results in a greater reduction in rooftop temperatures than water does alone.

Lastly, the comparison of the two roof systems showed that the temperature reduction determined by the extensive green roof was higher than that of the hydroponic roof by an average of 3 °C. However, it was observed that the hydroponic roof outperformed the extensive green roof in other significative aspects, such as excellent storm water storage, lower irrigation requirements and lower maintenance, due to the lack of a need to change the substrate, no damage to the roof slab by the plant roots, etc., easier installation and disassembly operations and easier weed control.

Studies with in situ measurements are an effective way to assess the thermal performance of construction technologies; however, in order to provide exhaustive data, a number of experiments should be conducted in all climatic zones, using the same methodology, defining a database of information to use as a guideline when designing a HGRS.

Experimental data are also useful to validate design models; however, studies that combine experimental and model approach for the assessment of thermal behavior of HGRS were difficult to find in the literature while conducting the present review.

An experimental/modeling approach was adopted in the study carried out by Tanaka et al. [18,19]. The researchers aimed at developing a model for assessing the heat balance of hydroponic roof systems and the subsequent thermal mitigation effects they determine. The experimental part of the study consisted in a hydroponic rice system (HRS) built on the concrete roof slab of a 30 m-high building in Osaka and monitored for a two-month period (July–August 2013). The rooftop used for the experimental setup was divided into two parts, with one covered with the hydroponic system (three 76 × 91 × 20 cm polyethylene open thanks) and the other one left bare. Water depth was kept at 10 cm so that the additional weight on the roof would not exceed the limit load (total extra load was about 80 kg/m^2).

For thermal characterization, field measurements of air, water and surface temperature were conducted, and conductive heat flux was assessed. Air temperature was also measured at 10 cm above the water. Data were collected at 10 s intervals and averaged into daily values. Weather data were also collected through meteorological sensors installed near the setup.

During the hottest period (from the 7th to the 22nd of August), the average daily maximum ambient air temperature was 32.8 °C and the average daily minimum ambient air temperature was 24.7 °C, while the highest value of daily mean solar radiation was 230 Wm^{-2} recorded in the period from the 6th of July to the 9th of August.

The experiment was also repeated the following year in Kyoto, during the same period (July–August 2014). Data collected during the experiment were then used to define mitigation indices for air temperature, surface temperature and conductive heat flux.

The thermal mitigation model was determined through three indices: normalized air temperature (NT_A), normalized surface temperature (NT_S) and conductive heat flux (G).

Air and surface temperature were assessed through Equations (1) and (2), respectively:

$$NT_A = -\frac{(T_G - T_B)}{(T_B + 273.15)}\ [K] \quad (1)$$

where T_G is the air temperature in the green roof area (°C) and T_B is the air temperature in the bare roof area (°C);

$$NT_S = -\frac{(T_W - T_S)}{(T_S + 273.15)}\ [K] \quad (2)$$

where T_W is the water temperature (°C) and T_S is the bare roof surface temperature (°C), while conductive heat flux (G (W m^{-2})) was determined through latent heat flux (lE (W m^{-2})) with Equation (3):

$$lE = \frac{(R_n - G - S)}{(1 + \beta)}\ \left[W{\cdot}m^{-2}\right] \quad (3)$$

where R_n is the net radiation (W m^{-2}), S is the water heat storage flux (W m^{-2}) and β is the Bowen ratio.

According to the results gathered, the average air temperature for the two months in the first year was 28.5 °C on the green roof area and 30.3 °C on the bare roof area, with an average difference of 1.8 °C ($p < 0.05$), while during the same months of the following year, the temperatures were 26.5 and 28.4 °C, respectively, with an average difference of 1.9 °C ($p < 0.05$).

It was observed that when thermal mitigation indices were defined only through latent heat flux, a uniform evaluation method could not be easily assessed. Therefore, a thermal mitigation factor was defined combining latent heat flux, conductive heat flux and water heat storage flux, which are the three heat balance factors. The assessment model for the thermal mitigation indices developed taking into consideration such factor was far more accurate. The results show that the assessment model proposed was able to estimate the thermal mitigation effects in terms of heat balance, regardless of the year.

The experimental results used by Tanaka et al. to develop the model were gathered, repeating the measurements in two different years and in two different cities (but with similar climatic conditions). In the same way, the model could be validated by applying it to results obtained in different climatic areas.

4.2. Passive Cooling Performance of Traditional Roof Gardens and Pond Roofs

In this review, studies on different passive systems' performance were analyzed in order to obtain qualitative and quantitative assessment of these systems' behavior and also to present the methodology used in the studies, which can be applied to further research.

Alexandri and Jones [23] conducted a study involving different cooling techniques for urban spaces, all focusing on the building roof. Four types of alternative roofing techniques were investigated and compared to the thermal performance of a plain concrete roof, used as the "base case". The four roofs studied were: (1) a concrete roof covered with a white coating; (2) a green roof with 20 cm vegetation; (3) a pond roof with 20 cm water (at 20 °C at midnight); and (4) a pergola with 20 cm vegetation, placed 2 m above the concrete roof.

The same four roofs were examined in three different climate conditions: (a) a hot and dry climate, using the climatic data of Athens; (b) a hot and humid climate, using the climatic data of Mumbai; and (c) a hot and arid climate, using the climatic data of Riyadh.

The measurements registered by Alexandri and Jones [23] for the four types of investigated roofs are gathered and summarized in Tables 2–4, referring to the three climatic conditions as listed above.

Table 2. Performance of the four roofs in the hot and dry climate (Athens) [23].

	Maximum Surface Temperature Decrease	Average Surface Temperature Decrease	Maximum Air Temperature Decrease (at 1 m)	Average Air Temperature Decrease (at 1 m)
Concrete roof covered with white coating	20.9 °C	12.4 °C	4.1 °C	2.2 °C
Green roof	26.2 °C	14.4 °C	7.3 °C	2.7 °C
Pond roof	28.1 °C	14.8 °C	4.2 °C	3.1 °C
Pergola	28.8 °C	15.6 °C	12.6 °C	8.1 °C

Table 3. Performance of the four roofs in the hot and humid climate (Mumbai) [23].

	Maximum Surface Temperature Decrease	Average Surface Temperature Decrease	Maximum Air Temperature Decrease (at 1 m)	Average Air Temperature Decrease (at 1 m)
Concrete roof covered with white coating	20.8 °C	11.7 °C	4.1 °C	2.1 °C
Green roof	27.6 °C	15.0 °C	8.0 °C	3.1 °C
Pond roof	27.8 °C	13.4 °C	5.5 °C	2.4 °C
Pergola	30.9 °C	16.8 °C	15.4 °C	10.6 °C

Table 4. Performance of the four roofs in the hot and arid climate (Riyadh) [23].

	Maximum Surface Temperature Decrease	Average Surface Temperature Decrease	Maximum Air Temperature Decrease (at 1 m)	Average Air Temperature Decrease (at 1 m)
Concrete roof covered with white coating	17.9 °C	10.4 °C	3.5 °C	1.9 °C
Green roof	29.5 °C	18.5 °C	8.8 °C	4.7 °C
Pond roof	22.9 °C	11.1 °C	4.6 °C	2.1 °C
Pergola	33.3 °C	21.0 °C	23.3 °C	17.6 °C

These tables show that the results vary depending on the climatic conditions of the site. In general, evaporating surfaces such as green and pond roofs work better than the white surface concrete roof in all climate conditions, with the pond roof performing slightly better than the green roof in the dry and humid climate but not in the arid climate of Riyadh, due to its raised temperatures and high solar radiation.

The results show that in the hot and dry climate of Athens, the evapotranspiration from plants was able to lower air temperatures significantly more effectively than a non-transpiring surface, which absorbs lower amounts of solar radiation.

It can be observed that the difference between the respective surface temperatures for the pond roof and the pergola (which performed best in all climates) was the greatest for the hot and arid climate of Riyadh, followed by the hot and humid climate in Mumbai, while it was significantly smaller for Athens' hot and dry climate.

In Alexandri and Jones' [23] study, the assessment of indoor temperature shows that all three roofs (pond roof, green roof and green sky) keep the physiological equivalent temperature (PET) value, i.e., the temperature perception that people have, within the "comfortable zone" for most of the day.

In terms of PET reduction, heat mitigation of hydroponic roofing systems can provide benefits not only to single buildings (indoor temperature), but can also guarantee positive effects on outdoor temperature at the urban scale and counteract phenomena such as the urban heat island (UHI) effect in urban areas, characterized by large non-permeable surfaces [3,23]. Alongside the increased summer temperatures, this phenomenon is amplified by the waste heat released by cooling devices used in buildings [18].

From the analysis of the results found by Alexandri and Jones (Figure 3), it is possible to draw significant information that can be applied to the further study of HGRS. For instance, focusing on the green roof and pond roof configurations, it can be noticed that, in hot and dry climates, both perform better than the white-coated concrete roof, with the pond roof performing slightly better than the green roof. On the contrary, in hot and arid climates, the pond roof provides a significantly lower temperature decrease since, despite the contribute of evaporation, as the amount of heat that gets stored in the water due to high temperatures and solar radiation causes the surface temperature to increase significantly at night.

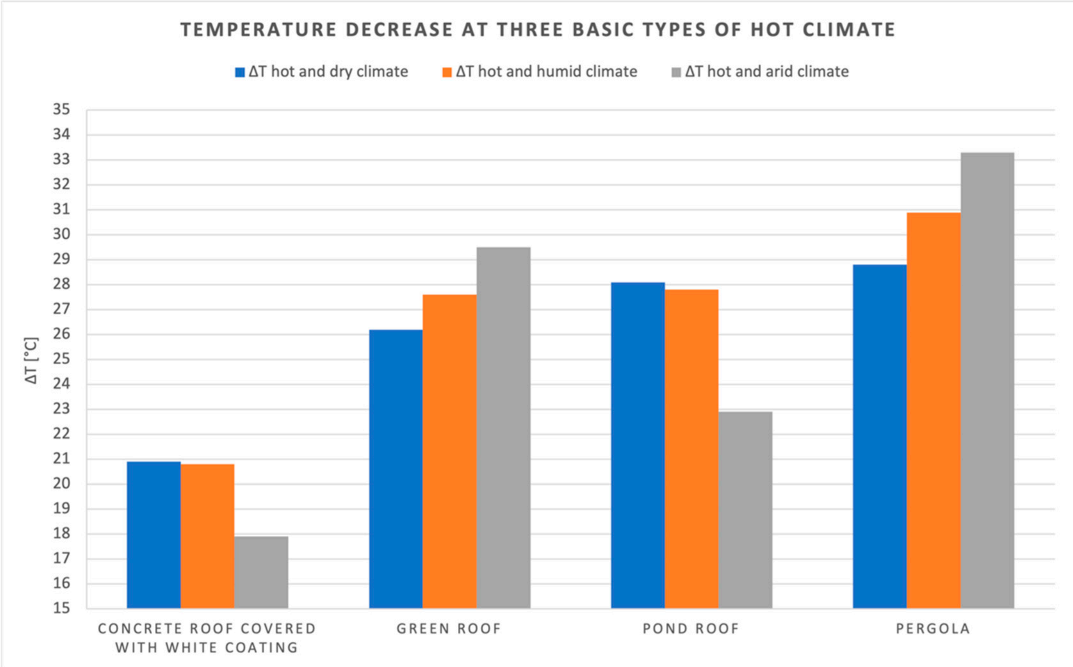


Figure 3. Temperatures decrease in three basic types of hot climate: hot and dry in Athens, hot and humid in Mumbai and hot and arid in Riyadh, with measurements repeated over the course of three years, in July for Athens and Riyadh and in May for Mumbai.

Alexandri and Jones' study shows that reproducing the same experimental analysis in different climatic conditions can provide more complete and exhaustive data. The results also provide information, not simply about which system is more efficient, but more specifically on which technique is more suitable depending on a series of correlated factors, such as the constructive nature of the building, dimensions, and indoor comfort requirements according to the use. It would be interesting to observe the behavior of a HGRS in the same conditions tested in the study, compare the results with the other system and assess if they are consistent with the expected outcome; for instance, if it is possible to design a HGRS that combines the benefits of the green roof and the pond roof configurations, overcoming the respective drawbacks.

Despite the lack of studies conducted strictly on HGRS as a design strategy for the passive cooling of buildings, many studies conducted on pond roofs can provide useful information to define a starting point for further investigations [35]. In the review process, results obtained from studies on pond roofs were analyzed, since they are considered comparable to HGRS in terms of physical characteristics, and therefore similar thermal behavior can be expected. The main difference between the two types is the presence of vegetation, which generally contributes to a further temperature reduction due to the heat released through evapotranspiration [3,53,54].

For instance, the potential cooling load reduction of HGRS can be improved when combining them with other systems, in the same way as has been done in the literature with pond roofs.

Almodovar et al. [6,22] performed tests on pond roofs combined with a water to air heat exchanger (WAHE), comparing the results obtained with and without the pond and with the WAHE system on and off. Their experiments were conducted in southern California, in a hot dry climate with mild winters. They used two 1.35 m × 1.35 m × 1.35 m test cells, oriented facing south-west: one with a floating insulating panel and a spray system operating at night, and one with a sealed flat aluminum plate, not directly in contact with the water tank but placed above it, with an air gap in between. Another cell, with a code-compliant roof, was used as "control cell" for results comparison. The support roof of both test cells is a metal deck, in order to provide good thermal coupling between the cell and the indoor air.

The roof of the first test cell has a 0.35 m-deep pond covered by a 3 cm polystyrene panel, with a spray placed 0.5 m above the pond, in order to provide evaporative cooling, with total U-value of 0.272 W/m^2 K. The insulation panel above the pond prevents water from overheating during the daytime, while the water is naturally cooled at night by evaporation and thermal radiation to the sky.

A WAHE system makes the indoor air recirculate through the pipes placed into the water tanks installed on the roof. This system uses water temperature to condition air inside the pipe and therefore indoor air temperature, thanks to water's high thermal capacity.

To improve efficiency and reduce the pond evaporation rate, the spray is only operated at night, since previous studies [55] have shown that when ambient temperature is higher than the pond temperature, the spray causes the water temperature to rise.

The roof of the second test cell has a 0.25 m-deep pond covered with an aluminum plate placed 10 cm above it, preventing water from evaporating, with a total U-value of 1.311 W/m^2 K. Cheikh and Bouchair [51] previously developed a dynamic mathematical model for roof ponds covered by an aluminum plate, which assessed the advantages of combining roof ponds with low emissivity materials, such as aluminum, but there is a lack of experimental tests to validate the model.

In the second test, the air inside the pipe placed into the pond is cooled by a fan inserted into the pipe, and the hot air from the cell is circulated through the pipe into the pond and exchanged into the water by conduction. The cooled air is then introduced into the test cell.

During the experiment, the dry bulb temperature, mean radiant temperature and relative humidity were monitored through data loggers.

In order to assess the effectiveness of the system, the described experiments were carried out on several pond variations, with the WAHE system on and off, and the results were compared with the control cell performance. We analyzed the results of four significant configurations: (1) a roof pond with floating insulation and sprayed at night, with the WAHE system off; (2) a roof pond with floating insulation and sprayed at night, the with WAHE system on; (3) a roof pond with an aluminum plate separated from the water by an air gap, with the WAHE system off; (4) a roof pond with an aluminum plate separated from the water by an air gap, with the WAHE system on.

In the cell with the insulated pond, the roof indoor temperature can be up to 8 °C less than outdoor temperature, reaching an 11 °C difference when the WAHE system is on.

In the cell with the aluminum roof, the maximum water temperature is higher than that of the cell with the insulated roof, showing that the insulation system keeps water at a lower temperature. The indoor and outdoor temperature difference is around 6 °C, reaching over 8 °C when the WAHE system is on.

In order to compare the results delivered by the different configurations, the measurements were normalized using the temperature difference ratio (TDR) (4) [22], which is defined by comparing the average reduction in the maximum temperature inside the cell with the average swing:

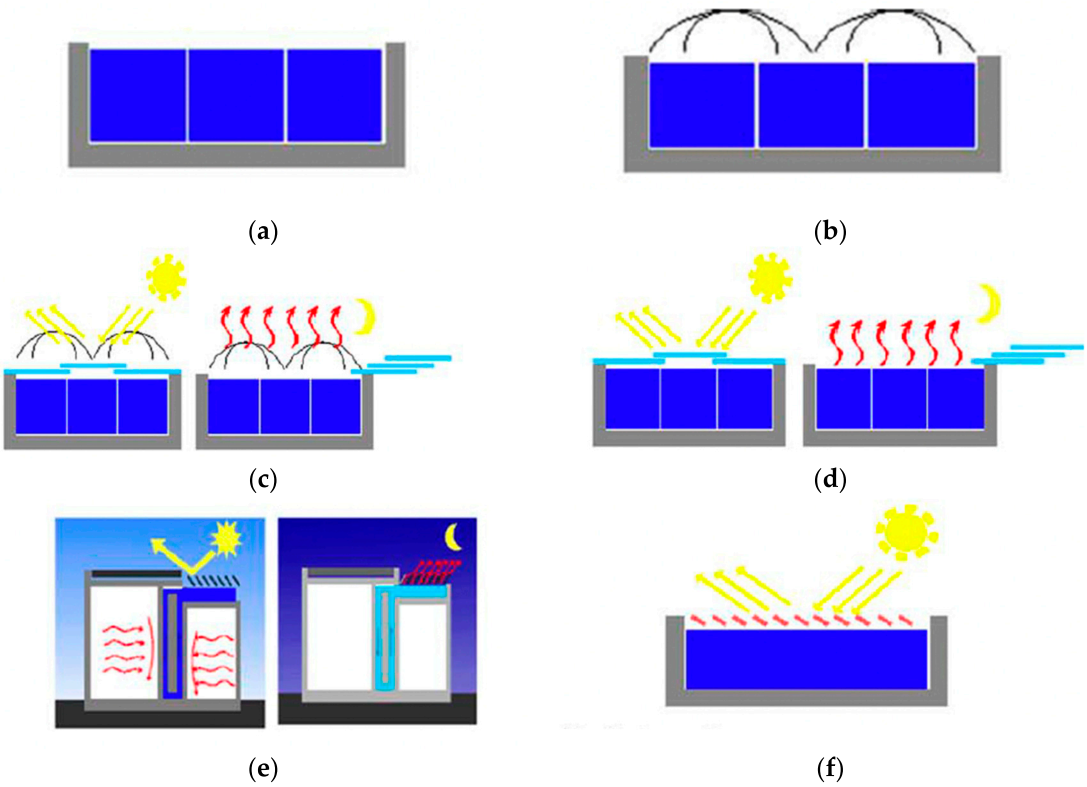
$$\mathrm{TDR} = \frac{(\mathrm{T_{max.amb}} - \mathrm{T_{max.cell}})}{(\mathrm{T_{max.amb}} - \mathrm{T_{min.amb}})} \quad (4)$$

with $\mathrm{T_{max.amb}}$ (°C), $\mathrm{T_{max.cell}}$ (°C), and $\mathrm{T_{min.amb}}$ (°C).

The results' comparison after using TDR shows how the experimental cells' performance was consistently better when the WAHE system was operating, especially for the insulated cell, which outperformed the control cell by 35%. Even though each configuration performed better in combination with the WAHE system, each pond roof performed better than the code-compliant controlled cell. From the experimental results, TDR can be used to predict the indoor maximum temperature, through the afore mentioned equation, as a function of outdoor maximum temperature and daily swing; then, by defining the heat exchange between the air and the water through the WAHE system, the latter can be dimensioned.

From this study, it can be observed how simple pond roof configurations provide more effective temperature reduction than traditional roofs, resulting in improved indoor comfort, which can be further improved by combining these roofs with systems such as WAHE. It is shown that the configuration that performed better was the pond roof with the floating polystyrene insulation, which is the most similar to a hydroponic system. For the purpose of this review, it is also important to note that the same experimental setup had been used two years prior, to study the cooling performance of the same WAHE system combined with green roof technology [6], which showed how the system could effectively provide cooling while reducing the energy consumption in buildings by using a water pond as a heat sink. Therefore, performing the same tests using a HGRS could be an interesting development of this study, perhaps integrating the WAHE with the water recirculation system for the hydroponic roof, taking into account the fact that the results from the previous studies represent significant data for comparison.

Since in the literature there are many variations of pond roofs, in recent years, various studies have focused on the comparison of their performance in order to assess which configuration is the most effective and whether the optimal configuration changes for different areas and climatic zones. Some of them performed quite similarly despite the difference in the operation. Spanaki et al. [41] conducted a study on the characterization of twelve pond roof systems with the aim of assessing the most effective design in terms of the evaporating cooling effect and therefore buildings' cooling demand reduction. Amongst the investigated variations, those considered the most significant in terms of similarity with HGRS are (Figure 4): (a) those uncovered without sprays; (b) those uncovered with sprays; (c) those covered with sprays; (d) those covered without spays; (e) cool-pools; (f) and shaded ponds.



(a) (b) (c) (d) (e) (f)

Figure 4. Different roof pond configurations: uncovered (**a**); uncovered with sprays (**b**); covered with sprays (**c**); covered without sprays (**d**); a cool-pool (**e**); and a shaded pond (**f**). Adapted from [41].

The uncovered roof pond without sprays (Figure 4a) is the simplest variant: it increases its temperature due to the solar gains until it is compensated by the spontaneous evaporation. Studies have shown that a roof covered with a simple pond can reduce its surface temperature by 20 to 30 °C, depending on the pond depth. The open pond variant usually guarantees higher peak roof temperature reduction than the spraying variant when RH reaches higher values (up to 80%), but does not perform as effectively for low RH values.

Uncovered pond efficiency is increased when sprays at constant temperature are added (Figure 4b): it is noticed that the maximum efficiency is achieved when sprays operate only at night, since this saves water and keeps the pond temperature from fluctuating around the wet bulb temperature (WBT). Additionally, sprays should not be operating when pond temperature is 3 to 4 °C above the ambient WBT, in order to prevent the water warming. This system works best for ponds less than 0.30 m deep, since for deeper ponds, the water temperature increase is not significant; however, uncovered ponds are susceptible to elements such as wind-blown dust, leaves, bird droppings, algae and mosquito larvae: in this sense, HGRS would overcome this problem, due to the presence of the board that holds the plants.

The covered pond with sprays and movable insulation during the day (Figure 4c) guarantees the reduction in temperature fluctuation in the pond and offers a higher cooling rate compared to the uncovered variation. The efficiency increases with higher conductance of the support roof, proving that the roof characteristics play an important role. The results observed for the covered pond without sprays (Figure 4d) show that water overheating is prevented by the cover, and furthermore, spontaneous evaporation decreases water temperature below the average ambient temperature. The pond performance is not affected by factors such as the covering emissivity, the solar absorptance of opaque covers and the ventilation in the space between the cover and the water surface. Tests have shown that the maximum indoor temperature is ~21.3 °C when the maximum outdoor is 27 °C: it was noticed that the pond roof can reduce the thermal load through the external surfaces from 41% to 66%. The experimental results show that the average cooling potential is 19.4 W/m^2 K from tests performed in August and 24.0 W/m^2 K from tests performed in January, corresponding to a daily removed heat of 465 and 577 Wh/m^2, respectively.

This type of pond roof is considered to perform best in arid climate conditions, where it can operate throughout the entire year. Studies [21,56] have reported that pond depths of 0.05 m to 0.10 m are enough to improve indoor comfort in arid climates.

The cool-pool (Figure 4e) is a type of pond roof where the water is cooled by a shading system of sloping louvers and then is circulated into a piping system in the building. Warmed water is then circulated back into the pond where it dissipates the heat through evaporation and is cooled again by the shading system. Maximum cooling is achieved at minimum RH values. Passive heating can also be achieved by placing the pipes behind south glazing and by blocking circulation with the roof pond. Shaded ponds (Figure 4f) are also based on the water cooling principle by preventing solar radiation from reaching the water, thanks to a permanent shading structure. Tests in hot and arid climates show that indoor building temperature can be maintained below 30 °C when the maximum ambient WBT is over 40 °C.

Aside from the pond, the similarity of HGRS with cool-pools and shaded ponds is the shading feature, which in the first is provided by vegetation.

The comparison of the different pond roofs characterized by Spanaki et al. [41] highlighted the different operation of these systems, which can be a deciding factor in the choice of which type to implement, at comparable efficiency, based on the use of the building, i.e., in some cases, water consumption may be the primary factor to consider, while in others, energy demand for automatization can be considered. For instance, a cool-pool system is a more sophisticated system but has higher efficiency in terms of water consumption, since the amount of heat removed per unit of water evaporated is higher compared to the other systems, especially in hot humid climates. On the other hand, variants such as the shaded pond require no automatization, but a larger area in order to be effective.

Other pond roofs were found to be efficient in the literature (e.g., skytherm and energy roofs) [41], but were discarded they are because non comparable to HGRS and/or were proven to be far more efficient when applied to metal roofs, which limits their application. Aside from these considerations, it is also important to take into account that each variant's performance varies depending on the specific climatic conditions (air temperature, relative humidity, etc.).

5. Rainwater Management and Water Quality Improvement

Even though traditional green roofs are effectively used as low-impact development (LID) techniques [5,19], for rainwater collection, storage and treatment, they present some disadvantages that can potentially be overcome by using hydroponic green roofs instead. As an example, traditional green roofs require thicker substrate layers to improve their runoff reduction ability, thus implicating significantly heavier green roof systems, which also implies greater maintenance requirements and irrigation during the dry months [57]. Subsequently, it is also reported that thicker substrates increased the risk of nutrient leaching [5,8], and added fertilizers can further compromise runoff water quality [58].

Xu et al. [20] studied the performance of a hydroponic roof developed for rainwater collection and greywater treatment in order to achieve water quality control.

The system developed by Xu et al., composed of seven tanks connected by a drainage pipe, was first studied from the point of view of rainwater collection, with greywater treated separately. The second phase of the experiment investigated the system's ability to simultaneously collect rainwater and treat greywater. The HGRS was monitored over a one-year period (September 2017 to August 2018) to investigate the effects on greywater treatment and urban storm water runoff reduction, with the aim of developing a model to actualize a sustainable use of water resources.

The experiment used synthetic greywater with a specific composition of chemical reagents in order to evaluate and compare the performances of several recycling processes on a reproducible effluent. During the first phase, over a three-month period, influent and effluent water samples were collected and tested; during the second phase, the system simultaneously collected rainwater and treated greywater. Eighty-one samples in total were collected during this phase over a 3-month period, and tested under light, moderate and heavy rain conditions.

The results show that the hydraulic retention time positively affects water quality. The effluent pH of each unit was lower than that the synthetic greywater pH. Their pH difference was smallest at 8 days of hydraulic retention time (HRT) and was kept stable over time.

Synthetic greywater turbidity increased consistently until, after peaking at 8 days of HRT, the final effluent decreased, meeting the standard. Additionally, COD and BOD_5 concentration in synthetic greywater increased to a peak value and then decreased, meeting the standard as well. Regarding bacteria presence, in the water samples, it was noted that some bacterial genera's abundance increased, indicating that they appeared over the course of the treatment. Other bacteria decreased compared to their initial concentrations, while others grew to a peak in the middle units and then decreased.

In the second phase of the experiment, in order to assess the ability of the HGRS to purify wastewater, rainwater was collected by the hydroponic roof and was then analyzed. It was observed that when the system collected rainwater and treated greywater simultaneously, and the effluent water concentration showed higher quality.

As previously stated, simulation models are a valid tool for predicting the system's behavior. This also applies to the assessment of hydrological performance for runoff volume reduction. This approach was used by Paithankar and Taji [5] for investigating the hydrological performance of green roofs. The aim was evaluating green roofs as hypothetic retrofitting strategies for sustainable storm water mitigation, from the perspective of a low-impact development (LID). The researchers applied a storm water management model (SWMM), which is widely used for hydrological simulations in urban areas, to two building blocks at a college campus in Kopargaon (Maharashtra State, India), with neither of the two having provision for stormwater management, which causes minor flooding during heavy rains.

The green roof on both building blocks was a 15 cm-deep extensive green roof, and was modeled defining the three main layers: vegetation, soil and drainage, although other parameters, such as the frequency and duration of rainfall events and site conditions, should be considered to reduce the error in the results and therefore provide more accurate correspondence with real-life applications, since they influence the green roof performance. In fact, even when computer models are used, they are often too simplified or neglect components that play a role in the assessment: for instance, many models that have been used to study green roofs' hydrological performance focus on a single aspect at a time instead [59].

In Paithankar and Taji's study, both single and continuous events were simulated, for the green roof as well as a traditional roof, for comparison. The theoretical model was obtained using dynamic wave routing, which considers backwater effects and solves 1D Saint Venant flow equations [60].

The results show that the implementation of green roof systems in existing buildings contributes to reducing storm water runoff by increasing the retention period. At the same time, studies on hydroponic systems have highlighted how these have the potential to perform better in rainwater runoff reduction, since in most cases they demonstrate better water holding capacity than traditional green roofs, especially when compared with extensive green roofs with low substrate depth. This occurs because the lack of solid material (substrate) in the hydroponic system provides more space to store water [20].

It is observed that, even though green roofs determine a significant improvement in terms of water runoff reduction, the organic percentage of the materials often used for the substrates can negatively affect water quality, due to the risk of nutrients leaching into water stream [8]. The implementation of HGRS can overcome this drawback, considering that in these systems, the solid substrate is missing.

The same SWMM methodology used in Paithankar and Taji's study can be applied in the assessment of hydrological behavior of HGRS, also allowing the performance comparison between the latter and traditional green roofs. Furthermore, more significant results would be obtained if simulation tools allowed more parameters to be considered.

6. Urban Agriculture and Mitigation of Crop Supply Impact

From the study of the current literature, it can be noticed how the potential environmental impact mitigation resulting from the implementation of HGRS does not only include resource saving on a building scale. In fact, on a wider scale, growing fruit and vegetables in urban areas would provide significant environmental benefits in terms of sustainable food production, determining higher food quality and lower transportation demand for fruit and vegetable supply. Therefore, implementing urban agriculture can contribute to mitigating environmental impacts in densely urbanized areas. However, studies on urban agriculture (UA) [61] show how the biggest issue with producing in metropolitan areas amounts of vegetables sufficient to comply with the daily intake is land availability. Hydroponic systems have been implemented as an efficient method within cities with very limited space available for harvesting crops. Studies on rooftop plant production (RPP) in urban areas pertaining to different culture systems have reported that hydroponic cultures provide the highest yield per unit area when compared to other agricultural methods, for any type of crop [62].

On this matter, Saha and Eckelman [63] carried out a study on actual and potential farming spaces in the city of Boston, MA, in the United States, also considering rooftops. The areas were identified and georeferenced through a GIS-based model especially developed for this aim. Their study identified approximately 922 ha of rooftop and 1250 ha of ground level lots, representing 7.4% and 10% of the total land area in Boston, respectively.

The results of this study show that if all of the available ground level lots were used for agricultural purposes and hydroponic systems were installed on all suitable roofs, Boston would be able to potentially annually produce a higher amount of high yield crops compared to conventional ground-based methods, considering a regular growing season.

The concerns with implementing hydroponic culture in building's rooftops pertain in most cases to the amount of energy necessary to operate these systems. Studies on the quantitative assessment of the resources needed for rooftop agriculture, from an LCA perspective, are present in the literature [64]; however, many more types of RPP systems should be evaluated in order to make a comparison. Furthermore, a greater number of variables should be considered, e.g., integrating in the LCA study an energy balance assessment between the energy needed to operate the system and the energy savings due, for instance, to the thermal isolation enhancement that it provides.

7. Modelling Approach

The energy performance of HGRS, as well as green roofs and pond roofs, depends on several different factors that need to be taken into consideration when designing the specific roofing system. For instance, climate parameters such as air temperature, relative humidity, rainfall, exposure, and overall climatic classification, which can be extremely different from area to area, significantly influence the performance of said systems. When these parameters are combined with the physical and chemical characteristics of the system's components (such as the type and thickness of substrate and drainage in GRs, water depth in HGRS and PRs, etc.), they determine a precise set of conditions that provide equally unique performance. For this reason, system modelling and energy simulation is an extremely useful tool for predicting the roof's behavior; however, significant results can be obtained when taking into consideration all of the variables simultaneously. For instance, GR models have been recently introduced in software libraries, such as DesignBuilder and Energy Plus; however, the model does not include specific parameters of all system components, e.g., a drainage layer is not included, vegetation parameters are not considered and soil characteristics are not customizable, showing that the model has not been significantly updated since it was first introduced [65].

Current models available for investigating different aspects of the studied system (thermal behavior, energy efficiency, hydrological performance, water management, etc.) are often too simplified or neglect aspects that play an important role in the assessment.

Ledesma et al. [50] conducted a simulation of a school building in Ecuador for evaluating the building's thermal energy performance due to rooftop farming, specifically addressing plant contribution, which is not typically included. They performed the simulation using Energy Plus for building energy modelling and MATLAB for crop modelling. The aim of the study was to a develop a model to leverage the transient flow exchange between crops and buildings by incorporating the plant's heat and mass balances in building simulation.

Crop energy balance was assessed independently in order to compare the performance of different systems (edible green roofs, hydroponic rooftop greenhouses and thermally integrated rooftop greenhouses), since vegetation can only be found embedded in the green roof model available in Energy Plus. Crops were simulated using three sub-models: (1) growth, (2) canopy energy balance and (3) net photosynthesis. Starting from the green roof model module available in Energy Plus, parameters were added and/or adjusted. Dynamic LAI and plant height data were included; however, it was not possible to modify soil's thermal characteristics. The results show that LAI plays a key role in energy balance, and therefore using a dynamic LAI parameter would produce noticeably different data, increasing accuracy.

In general, all systems improved indoor thermal comfort; however, experimental studies to validate the method should be conducted.

Research results from studies using a modelling approach show that even if simulation software is a valid tool, it needs to include a wider set of input data in order to provide more accurate information.

Detailed models would also allow us to effectively predict cost-effective best practices and technologies [66].

8. Discussion and Future Development

The analysis of various studies conducted on hydroponic green roofs highlights the key factors to take into consideration for implementing these systems and providing a better understanding of the potential effects determined by them in correlation to the boundary conditions.

8.1. Passive Cooling Properties

In this review, we attempt to compare the results gathered, to provide an organic view on HGRS, despite the lack of studies that follow the same methodology. The comparison between the study carried out by Huang et al. [12] and the one conducted by Alexandri and Jones [23] shows that the difference in their findings most likely depends on the climate in which the experiments were conducted: for instance, comparing the results gathered by Huang et al. in Athens, it can be observed that the climate of Athens in July is hot and dry, with a relative humidity of about 50%, while the climate of Taichung in September is hot and humid, with a relative humidity of about 80%. These values implicate a greater rate of evaporation of water in the roof in Athens, which helps to reduce excessive heat on the roof surface. This result is consistent with the findings of Perini and Magliocco [3], who observed that vegetation is more effective with higher temperatures and lower relative humidity values in mitigating temperatures.

A significant finding in Huang et al.'s study shows that when the average air temperature was 30.72 °C, the average surface temperatures of the hydroponic roofs at 10, 20 and 30 cm were 30.98, 31.11 and 31.06 °C, respectively, indicating that no significant discrepancies in measurements were determined by the different water depths. In general, it was noticed that, in the same conditions, all three water depths provided a rooftop temperature reduction of approximately 5 °C on average, and a maximum of approximately 15 °C.

The numerical assessment of thermal mitigation provided by HGRS carried out by Tanaka et al. [18,19] was the only study that aimed to define a prediction method for the mitigation effect on thermal environment based on the statistical correlations between the mitigation index and net radiation, latent heat flux, thermal mitigation factor, observing that when net radiation increased, so did the air temperature decrease ratio. Furthermore, the calculation of the coefficient of determination between net radiation and surface temperature mitigation index showed that surface temperature decrease ratio increased with the increase in net radiation.

The results of experimental studies conducted on different configurations of pond roofs [22,23,25,26,35,41] contribute to the advancement in the research of HGRS by providing information regarding common characteristics of both systems, starting with the thermal behavior of the water component, both in terms of water depth and contribution of evaporation. Consistently with the results of Huang et al., several studies on pond roofs show that these systems can provide significant thermal insulation even at shallow water depths and the temperature reduction does not increase proportionally with the increase in water depth [12,21,41,56]. Furthermore, greater water depths may increase the evaporation rate per unit volume, subsequently increasing daily cooling requirements, as opposed to shallower ponds, which would extract more heat from the roof instead [26]. The most debated drawback of pond roofs is their behavior during cold months; analysis of covered ponds showed that they are also able to provide heating load reduction during the wintertime, but they are less effective at significantly low temperatures (below 5 °C) [35]. Best results during cold periods are in fact achieved in regions with mild winter temperatures [35]. Further assessments on HGRS thermal behavior can be conducted based on the findings regarding the roof pond variations that are most similar in terms of construction: pond roofs with floating insulation, ventilated pond roofs, and shaded pond roofs [35,41].

8.2. Rainwater Management and Water Quality Improvement

The assessment of water concentration in a hydroponic green roof collecting rainwater and/or treating greywater carried out by Xu et al. [20] shows how a HGRS can significantly reduce the organic matter presence, turbidity, and anionic surfactant concentration, as well as effectively collect rainwater and treat greywater, guaranteeing low operating costs, smaller volume density, providing overall positive ecological benefits. Analyzing the concentration trends, the results show that in general, when the system both collected rainwater and treated greywater, the COD, BOD_5, and anionic surfactant concentration in the effluent were lower than when greywater was treated separately, resulting in superior water quality.

Alongside the quantitative assessment of pollutants reduction, these systems have a greater potential than traditional green roofs to mitigate urban flooding, since they allow the water level to be reduced before rainy events, enabling up to 90% runoff recovery of rainwater with an intensity of around 200 mm/d. Even extensive green roofs, which have a higher water storage capacity than traditional ones, do not guarantee the same water management, since they are not usually designed with greywater treatment units, and therefore when no rainfall occurs, they need to be irrigated with tap water.

Additionally, in comparison to extensive green roofs, HGRS require less substrate material while still providing higher water storage capacity, which implicates a greater ability to collect rainwater, but at the same time reducing the load on the roof, due to the lower bulk density of a hydroponic system compared to a green roof system with the same volume. The HGRS analyzed, composed of 25 cm of water, ceramsite substrate, containers and plants, carries a load of 156 kg/m^2, which is lower than the 200 kg/m^2 calculated for an extensive green roof.

8.3. Further Environmental Benefits

Potential mitigation effects of environmental impacts provided by HGRS are not just limited to the reduction in buildings energy consumption due to passive cooling and heating, but also include resource control from a life cycle assessment (LCA) perspective, considering both fewer new resources being required for the operation of these systems compared to traditional ones, and the potential reuse of resources, such as wastewater resulting from other activities, as investigated in Jiménez-Arias et al.'s study [30].

Other environmental issues can benefit from the use of HGRS; studies have shown how the implementation of rooftop hydroponic systems for urban agriculture has the potential to exponentially reduce land use and water used for field irrigation (due to high water retention capacity), while at the same time increasing food production, promoting crop harvesting in urban areas, indirectly reducing pollution caused by transportation. The results from the study conducted by Saha and Eckelman on this matter [63] show that if all of the available areas in Boston were used for agricultural purposes and hydroponic systems were installed on all suitable roofs as well as ground level areas, the city would be able to potentially annually produce nearly 17,000 tons of high-yield fruits and 180,000 tons of high-0yield vegetables. The possibility of promoting fruit and vegetable production in urban areas therefore contributes to a sustainable food production chain, in terms of lower transportation demand for fruit and vegetable supply, providing a higher food quality at the same time [16,29].

8.4. Knowledge Gap and Potential Developments

As emerged from this review, research on HGRS as mitigation strategies against environmental impacts of buildings is currently limited, and very few studies can be compared. Nonetheless, significant inputs derive from numerous analyses conducted on green roofs, pond roofs and other systems designed to achieve the same performance, which are consolidated as constructive techniques, but are still trying to overcome a few drawbacks.

The first attempts at assessing the thermal behavior and cooling effect of HGRS show that they are able to provide performance comparable to those systems.

The research should take a multidisciplinary approach in order to assess these systems' efficiency in light of their benefits pertaining to different sectors.

In fact, from the results gathered through the literature review, it can be observed how HGRS's potential benefits concern different aspects, such as thermal insulation as well as hydrological management, urban agriculture. Furthermore, the contextual study of multiple aspects is necessary because in most cases they are not independent but rather connected (e.g., energy efficiency, mitigation of environmental impacts, water recycle, etc. [67]), achieving a greater efficiency in terms of circular economy [68].

At the urban scale, when considering that topics such as food production and stormwater management are both primary issues for all cities, addressing them with a holistic approach helps to increase efficiency.

On this matter, computer models provide a tool for a holistic approach in the study of HGRS, allowing us to assess their performance while taking into account all contributing factors; however, the majority of simulation software lacks accuracy when it comes to modeling less conventional systems, due to the lack of specific parameters and characteristic to add as input data. Nonetheless, in situ experiments in different cities and different climatic areas are necessary to validate computer models and are important for setting a trend in their behavior at various conditions and, subsequently, providing the input data to consider in the design process.

9. Conclusions

The analysis of researchers' findings regarding the topic of HGRS carried out in this paper aims to gather the knowledge on these systems in order to propose them as potential alternatives to traditional green roofs and pond roofs, in terms of construction technology for environmental impacts mitigation. Several aspects were investigated despite the limited number of studies currently present in the literature. In particular, thermal behavior, passive cooling/heating performance and rainwater management ability were investigated in the first place. Hydroponic systems have been mostly studied as alternative cultivation methods for growing crops in urban areas, where the lack of available land limits agriculture practice. Even though this study focuses on the technical performance of hydroponic systems implemented in buildings roofs, studies on UA add value to the potential use of HGRS, offering further environmental benefits in terms of efficient crop production with less resource consumption and transportation needed to cater food supply from extra-urban areas, from an LCA perspective. This shows that an interdisciplinary assessment is needed in order to provide an all-round view of these systems' potential benefits.

As energetically efficient passive designs, hydroponic roofs provided better performance than traditional roofs in all of the reviewed studies, while they showed similar results compared to extensive green roofs, outperforming them in several circumstances and different areas. The presence of vegetation provides further temperature reduction, enhancing the passive cooling potential of pond roofs thanks to the heat released through evapotranspiration. However, the cooling effect increase due to plants is more or less significant depending on climate conditions; the maximum temperature decrease is usually obtained at higher temperatures and lower RH (arid climate), while at high RH values, evapotranspiration's contribution is less effective.

Experimental tests carried out by authors show that HGRS provide a high temperature reduction during daytime, compared to the temperatures of the support roof without the hydroponic system, while reaching slightly higher temperatures at nighttime, because of the delay in heat transfer to the roof, due to water's high heat capacity. In fact, it was also observed that the time lag between peak air temperature and peak surface temperature is greater for HGRS. The maximum temperature reduction reported by the authors is over 20 °C, with significant differences between tests conducted in different climates.

Potential integration of HGRS with techniques such as WAHE systems and others that have been studied in combination with pond roof systems, as previously discussed in this paper, can deliver high efficiency buildings, even without the need for extremely sophisticated technologies: it is significantly easier and cheaper to build and maintain a hydroponic green roof system than an extensive green roof system, due to its limited number of components and simplicity of operation. Nonetheless, mechanically advanced systems can be designed. Furthermore, problems such as weed species, loss of soil fertility and root damage to the roof are unlikely to arise in a hydroponic green roof system.

Even in conditions where hydroponic green roofs do not outperform in terms of temperatures decreasing, the implementation of these systems as an alternative to traditional green roofs is also motivated by several further advantages, such as efficient rainwater runoff management, as well as environmental benefits derived from the implementation of HGRS for improving urban agriculture strategies.

The ease of assembly was observed by Tanaka et al. while installing the setup for the experimental phase of their study, since they found that the HRS was both easier to install and remove compared to the pond roof, also tested during the experiment, and it was simpler to adjust the system layout according to the user needs.

Likewise, Huang et al. stated that is easier to install a HGRS than an extensive green roof and the cost/benefit ratio of the first is higher considering that a plant species that can grow in a 10 cm water layer would need a much thicker layer of solid substrate. Authors have addressed the weight issue by assessing the weight of their experimental setup (Tanaka et al.) or comparing it with that of other systems (Xu et al.); however, no studies focusing on a thorough assessment of such aspects were found.

Authors' findings on HGRS performance open up possibilities for future developments; however, in order to state that they represent a viable alternative in the search for energy efficiency and environmental impact culling, some aspects should be further investigated, filling the current knowledge gap, such as construction and maintenance cost, since so far, only qualitative assessments have been carried out or have been superficially addressed, and the weight issue, as mentioned. A quantitative assessment of these aspects is key to establishing the overall higher performance of HGRS compared to extensive green roofs and pond roofs.

Additionally, further research should be carried out taking into consideration all variants, with regard to the characteristics of both the building and the site of installation. Extensive studies of hydroponic green roofs can lead to the establishment of these systems as common practice in the field of sustainable and low-impact constructions. An experimental/model methodology should be adopted in order to validate the findings and provide more accurate results. A more complete and reliable set of information could be achieved if future studies applied this approach.

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Nomenclature

HGRS	Hydroponic green roof systems
iRTGs	Integrated rooftop greenhouses
BIA	Building integrated agriculture
UHI	Urban heat island
UA	Urban agriculture
CEA	Controlled environment agriculture
LCA	Life cycle assessment
NFT	Nutrient film technique
DWC	Deep water culture
RH	Relative humidity
PET	Physiological equivalent temperature
NT	Normalized temperature
LID	Low-impact development
HRT	Hydraulic retention time
BOD_5	Five-day biochemical oxygen demand
COD	Chemical oxygen demand
DO	Dissolved oxygen
WAHE	Water to air heat exchanger
TDR	Temperature difference ratio
WBT	Wet bulb temperature

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