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Wetland Roofs as an Innovative Solution for Sustainable Urban Development

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Abstract

Wetland roofs provide an innovative solution for sustainable urban development, addressing challenges such as limited green spaces, climate change impacts, and urban water management issues. These specialized green roofs feature a permanent water element and wetland vegetation, providing enhanced ecosystem services compared to conventional green roofs. Key benefits include effective stormwater management, greywater treatment, significant cooling effects, and increased biodiversity. Wetland roofs also offer socio-economic advantages by utilizing rooftop spaces, improving aesthetics, and providing long-term cost-effectiveness. Despite requiring active water management and having higher structural demands, successful global implementations demonstrate their functionality and durability. Continued research is vital to optimize design, address knowledge gaps, and promote wider adoption of this multifunctional green-blue technology in urban planning.

Keywords: wetland roofs, sustainable urban development, stormwater management, greywater treatment, urban heat island

1 Introduction

Urban areas increasingly experience pressure from climate change, extreme rainfall events, heat stress, and limited space for green-blue infrastructure. Although conventional green roofs provide several environmental benefits, their performance is often constrained by dependence on precipitation, low evapotranspiration during dry periods and the low physiological activity of succulent species typically used [1–5]. Standard systems also cannot treat greywater and offer only limited contribution to urban biodiversity.

Wetland roofs integrate a permanent water element and hydrophilic vegetation, enabling continuous evapotranspiration, enhanced cooling and significantly higher ecological value. Their stable water regime, faster vegetation development, and potential for greywater treatment position them as a multifunctional nature-based solution combining retention, thermal regulation, and habitat creation [5,7–10].

Scientific knowledge on wetland roofs remains fragmented, with most studies limited to isolated case examples and lacking systematic comparison with conventional green roofs [5,8-

12]. This review therefore summarizes current knowledge, compares the functional performance of wetland and extensive green roofs, and identifies research needs to support future applications in sustainable urban development.

2 Methods

This review is based on a structured search of literature and technical sources addressing the concept, design and performance of wetland roofs. The primary literature search was conducted in the Scopus, Web of Science and Google Scholar databases using predefined keywords such as "wetland roof," "marsh roof," "hydroponic roof," "roof constructed wetland," and "multifunctional green roof." Only publications directly investigating rooftop wetland systems or roof-based constructed wetlands were included. Studies focusing solely on conventional green roofs were excluded unless they provided relevant comparative context.
A total of 18 scientific papers meeting the inclusion criteria were identified, including four review papers. Because wetland roofs represent a highly specific and still emerging ecotechnology, the number of peer-reviewed scientific publications worldwide is limited. For this reason, supplementary professional and technical resources were also incorporated, including engineering reports, implementation guidelines, and specialized webpages (e.g., Ingenieurbüro Blumberg, mokradni-strecha.cz) that document practical experience and realized case studies not yet available in scientific databases.
This combined methodological approach reflects the current development stage of wetland roof research and ensures that both academic findings and practice-based knowledge are represented in the review.
To ensure a consistent comparison of available studies, the effectiveness of wetland roofs was interpreted using commonly applied performance indicators. Stormwater management was evaluated through retention capacity and runoff delay, thermal performance through surface temperature fluctuations and evapotranspiration, and greywater treatment through standard water quality parameters (BOD_5, COD, TSS, TN, TP, NH_4-N). These metrics represent widely used evaluation criteria in green roof and constructed wetland research and enable synthesizing findings from heterogeneous case studies.

3 Results

3.1 Definition and characteristics of a wetland roof

A wetland roof is a specialized type of extensive green roof characterized by the permanent presence of water and hydrophilic vegetation. Its layering resembles a single-layer extensive green roof [6], but with a continuous water source. Wetland roofs may be flat or sloped, substrate-based or textile-based, and rely either on irrigation systems or a maintained water level. Two typical configurations are shown in Figure 1.
Flat systems require overflow elements to avoid structural overloading. If only part of the roof is designed as a wetland, a framed section must be added and protected against winter ice. All variants require a root-resistant waterproof membrane, geotextile and pond liner. The growing medium must be lightweight and provide sufficient hydraulic retention time when used for water treatment [7].

For roofs with limited load-bearing capacity, textile mats (e.g., Rhizotech, ZinCo) offer low bulk density and adequate rooting depth [5]. The vegetation consists of hydrophilic species with high evapotranspiration, fast establishment and strong resilience [8], selected according to local climatic and functional requirements.

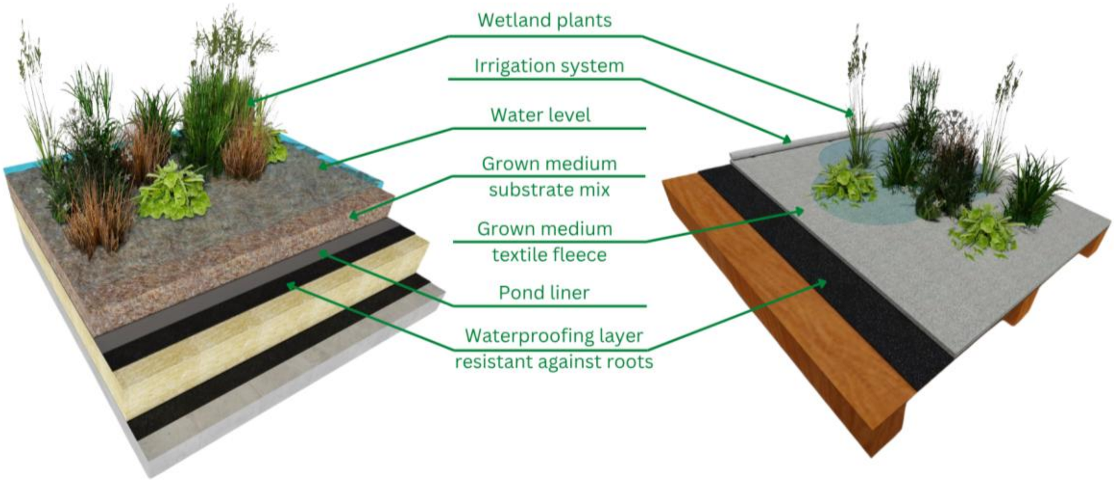

Figure 1: Layer composition of two wetland roof variants: a flat roof with a water layer and substrate mixture, and a sloped roof with an irrigation system and textile-based growing medium. The comparison illustrates the design flexibility of wetland roofs for different structural and hydraulic conditions [Source: Author]

For roof variants that resemble a rooftop pond or marsh, overflow openings or drains are required to prevent structural overloading during periods of excess water. If only a portion of the roof is designed as a wetland, a framed section must be created, and the parapet or frame needs to be protected against potential winter ice expansion, for example, by using tapered insulation along the perimeter.

The entire roof area beneath the wetland system must be finished with a root-resistant waterproof membrane. A layer of geotextile and pond liner is then installed. The substrate-based growing medium should be lightweight enough to stay within the load-bearing limits of the roof structure, while also providing adequate hydraulic retention time if the system is used for water treatment [7]. The substrate mixture may include crushed stone (grain size 0–16 mm), peat, topsoil, mineral soil, sand, and gravel. Polylactic acid beads and lightweight expanded clay aggregates have also been tested due to their low weight and ability to promote surface biofilm development [5,8].

For sloped or structurally limited roofs, a variant utilizing a textile-based growing medium is recommended. These mats must provide sufficient rooting depth and hydroaccumulation capacity (e.g., Rhizotech mat, ZinCo mat) [5]. In this case, traditional substrates such as sand, gravel, or soil are not used. Due to their low bulk density, these mats are well-suited for roofs with limited load-bearing capacity.

The final layer consists of vegetation made up of a diverse range of hydrophilic plant species, which are known for their high physiological activity, greater evapotranspiration capacity, and natural resilience [8]. Plant selection should be tailored to the specific environment of the intended roof site. Criteria for plant selection include ease of cultivation, resilience in harsh

conditions, capacity for wastewater treatment, aesthetic appeal, full roof coverage potential, low cost, and availability.
Figure 2 shows the progression of vegetation coverage in extensive green roofs with substrate depths of 120 mm and 240 mm, compared to a wetland roof from the experimental rooftop installation in Košice (Slovakia). The extensive roofs were planted with traditional species intended for extensive green roofs, and vegetation coverage was documented at planting, and then after 1, 2, and 3 years. Nearly full coverage was achieved after three years. In contrast, the wetland roof exhibited much faster vegetation development, coverage was documented at planting, then after one month, six months, and one year. Wetland plants rooted and spread significantly faster than those on conventional green roofs.

Figure 2: Development of vegetation cover on an extensive green roof and a wetland roof from installation to full coverage. The comparison highlights the considerably faster establishment of wetland vegetation under stable water availability [Source: Author]

A wetland roof does not necessarily need to cover the entire rooftop area; it can be integrated as a partial feature within a conventional green roof. This enriches the rooftop with a dynamic water element, contributing both to its aesthetic value and to biodiversity. For instance, a biodiverse green roof was implemented on the northern terrace of an administrative building in Košice, incorporating a wetland roof feature. Since the project involved an existing structure, the wetland element was positioned above the smallest module of the building's frame, where the columns and beams are spaced 3.2 meters apart. Figure 3 displays a photograph of the northern biodiverse roof two months after implementation.

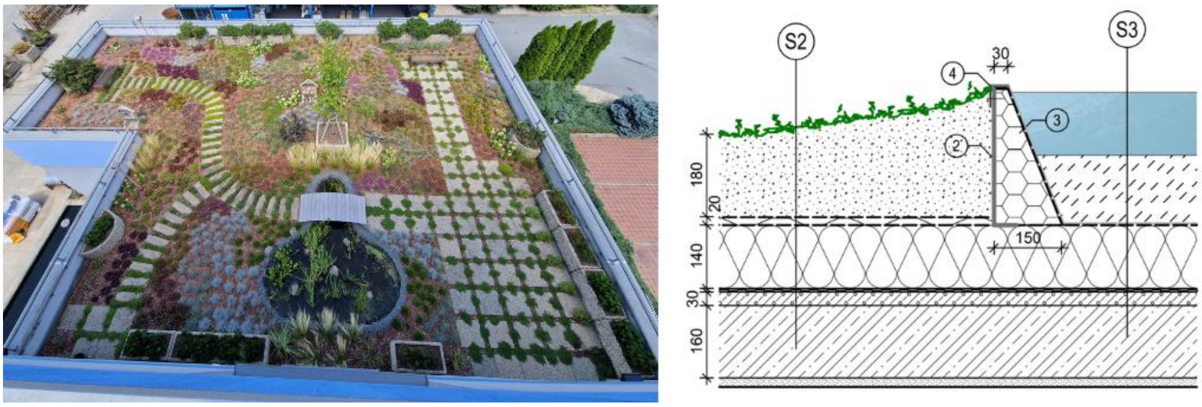

Figure 3: Integration of a wetland element into an extensive green roof within the greenIZOLA project, accompanied by a schematic representation of the connection between the wetland unit and the surrounding roof. The configuration enhances structural diversity and supports rooftop biodiversity [Source: Author]

3.2 Multifunctional benefits

Wetland roofs provide the same general advantages as conventional green roofs but with several more pronounced effects due to permanent water presence and hydrophilic vegetation. They enhance urban water management, support greywater treatment, improve cooling, and significantly increase ecological value compared to traditional extensive systems.

3.2.1 Urban water management

Similar to natural wetlands, wetland roofs are highly effective in managing stormwater. Studies indicate that wetland roofs can retain over 90% of rainwater, releasing it gradually through evapotranspiration or slowly via the roof's drainage system. These significant delays runoff into sewer systems, thereby helping to prevent urban flooding and sewer overflows.

One of the primary functional benefits and a key commercial attribute of wetland roofs is their ability to treat greywater, functioning as rooftop constructed wetlands [5,7,8]. This decentralized approach offers a sustainable and eco-friendly alternative to traditional, energy-intensive, and costly centralized wastewater treatment plants. Wetland roofs act as natural filters, removing pollutants and sediments from water as it passes through the vegetation and substrate. Plants and microorganisms within the wetland assist in breaking down and absorbing contaminants, thus improving overall water quality. By integrating wetland roofs into urban infrastructure, the quality of stormwater runoff can be improved, leading to cleaner water entering surrounding ecosystems.

Research focused on greywater treatment using wetland roofs is still limited. However, the Helmholtz Centre for Environmental Research in Germany has been actively exploring this topic [9,10]. Additional studies have been conducted in China [11], Korea [12], and Vietnam [13-15]. All of these studies reached a common conclusion: wetland roofs are effective in water purification. A comparative summary of treatment performance based on these studies is presented in Table 1.

Table 1: Efficiency of greywater treatment with a wetland roof - comparison of selected research

Parameters	Germany		Vietnam			China
	[9]	[10]	[13]	[14]*	[15]*	[11]
BOD5	98.9%	96%	-	-	-	97%
COD	93.5%	93%	78%	70%	54%	81%
TSS	-	94%	-	-	-	-
NH4-N	-	84%	-	-	-	-
TN	96.2%	71%	75%	87%	72%	-
TP	77.6%	87%	62%	89%	56%	-
AS	-	94%	-	-	-	88%
TR	-	-	-	-	-	75%
*Results are selected from the best variant of the experimental wetland roof						

3.2.2 Climate regulation and energy efficiency

Conventional green roofs help moderate surface temperature fluctuations through the higher albedo (reflectivity) of vegetation and, most importantly, via evapotranspiration, which removes thermal energy from the surrounding environment. Wetland roofs amplify this effect due to the permanent presence of water and the use of wetland plant species, which are physiologically more active than succulents.

By capturing and retaining large volumes of rainwater, a wetland roof keeps water on-site as an active part of the ecological water cycle. The more water that remains on the roof, the greater the potential for evapotranspiration. Additionally, wetland plants exhibit significantly higher evapotranspiration rates than terrestrial plants, particularly when compared to succulents, which are commonly used in extensive green roofs. The evapotranspiration rate for wetland vegetation typically ranges from 5 to 9 liters per square meter per day. The combination of constant water presence and active wetland vegetation is likely to generate an even greater cooling effect than traditional green roofs, helping to lower surrounding air temperatures and cool the underlying building structure.

Both laboratory and field measurements demonstrate that roofs with wetland layering regulate and stabilize rooftop temperatures more effectively than traditional or even green roofs. For instance, a temperature difference of up to 25 K was recorded between a pilot wetland roof and a gravel roof in Germany [8,16]. When implemented above the cattle shed, a wetland roof reduced the interior temperature beneath the roof by 5 K [8,17].

In Košice (Slovakia), a daily temperature fluctuation of 3-5°C was observed at the waterproofing layer of a wetland roof, compared to a 10°C fluctuation in a conventional green roof during summer months. The maximum surface temperature beneath the vegetation on the wetland roof reached 28°C, while on the green roof it reached 41°C [18]. On hot summer days, the water temperature in the rooftop wetland remains lower than the surrounding air temperature. Karczmarczyk et al. [19] recorded that the average water temperature of a wetland roof was 5.2°C lower than the air temperature on the hottest day.

3.2.3 Biodiversity and Ecological Enhancement

A wetland roof contributes significantly to increased biodiversity, primarily through its lush vegetation and the potential presence of fauna, particularly insects. Wetland plant species play

a crucial role and offer several ecological advantages over the typical terrestrial vegetation used in conventional green roofs.
Wetland plants are known for their exceptional resilience, as they can tolerate both periods of drought and flooding without sustaining major damage. Moreover, these plants exhibit high physiological activity, meaning that a wetland roof can produce significantly more oxygen through photosynthesis compared to a typical green roof. Additionally, wetland vegetation is highly effective at filtering airborne dust and particulate matter, thus improving air quality to a greater extent.

3.2.4 Socio-economic and aesthetic benefits

A key advantage in increasingly urbanized areas with limited land availability is the ability to utilize rooftop spaces, thereby avoiding competition for valuable ground-level plots. This enables the implementation of water treatment systems and green infrastructure without land-use conflicts. The lush vegetation of wetland roofs offers considerable aesthetic benefits to buildings and their surroundings, fostering a stronger connection between urban environments and nature. These visually appealing green urban spaces contribute to resident well-being and provide opportunities for recreational activities.
While the initial construction costs of wetland roofs may be higher than those of conventional roofs, they can be more cost-effective over their lifetime due to energy savings (reduced need for heating and cooling) and an extended lifespan of the roofing membrane. Wetland roofs protect the roof structure from extreme temperature fluctuations. UV radiation does not directly affect the waterproofing layer, as it is intercepted by dense vegetation and potentially by a water surface. Furthermore, wetland vegetation provides shading, which contributes to temperature regulation.

3.3 Barriers

Although wetland roofs represent an innovative solution within the field of blue-green infrastructure, their implementation and operation involve several limiting factors that must be considered during the design phase.
One of the main operational constraints is the need to control irrigation systems or water levels. Unlike extensive green roofs, which primarily rely on natural precipitation, wetland roofs require an active water regime. Maintaining appropriate water levels or ensuring a regular supply of greywater or rainwater is essential for the viability of the vegetation and the overall functionality of the system. In practice, this necessitates the installation of irrigation and monitoring equipment, which in turn requires technical maintenance.
This is closely linked to the energy demands of the system. The operation of automatic irrigation, water level regulation, and possibly pumps and sensors requires a continuous supply of electrical power. This can be problematic, especially in buildings with limited access to the power grid or in cases where the design goal is to minimize the building's overall energy consumption.
Another challenge is the load-bearing capacity of the structural system. Wetland roofs designed as permanently flooded systems (ponds/marshes) have a significantly higher weight compared to standard extensive green roofs. As a result, structural requirements are more stringent, which may limit the feasibility of implementing wetland systems, particularly on existing buildings lacking sufficient load capacity.

From a practical standpoint, the pre-cultivation of vegetation is crucial for the successful establishment of plants in rooftop conditions. Wetland plants require a period of acclimatization and root development, so it is recommended to pre-grow them for at least one growing season prior to final installation. This extends the preparation time and may increase implementation costs.
Lastly, a major barrier is the low level of awareness and experience with this type of solution. Wetland roofs are still a relatively new concept, and the market lacks sufficient knowledge among investors, designers, and contractors. The lack of professional expertise may result in design or construction errors, ultimately reducing the system's effectiveness and lifespan.

3.4 Case studies and research on wetland roofs worldwide

Case studies were included based on documented implementation and the availability of performance data on stormwater retention, cooling or greywater treatment. As wetland roofs are still rare, all verifiable examples from scientific or technical sources were incorporated to represent the full spectrum of real-world applications across different climates and functional contexts.
One of the earliest and largest installations is the 3,000 m² wetland roof at the Possman Cider Winery in Frankfurt (1991), which has been operating for more than 30 years and serves as a natural cooling system for storage facilities while providing substantial ecological value [8]. Another long-term example is the 160 m² wetland roof at the John Deere Tractor Factory in Mannheim (2001), designed for phosphorus removal from process water, demonstrating long-term nutrient reduction efficiency. A similar application is the 834 m² wetland roof at the Federal Agricultural Research Centre (FAL) in Braunschweig, which reduced interior barn temperatures by 5 K and effectively mitigated heat stress in dairy production [16].
Smaller-scale systems demonstrate the potential for decentralized greywater treatment. A private house in Prague integrates a wetland roof as a tertiary treatment stage after primary septic tank purification, enabling water reuse for irrigation and flushing [20]. A comparable system operates at the Charles Darwin Foundation in the Galápagos, where a rooftop wetland is used to irrigate the research station's vegetation following two-stage constructed wetland treatment [21].
Textile-based systems have been successfully implemented on sloped roofs, for example, in Jena (Germany) and Zofingen (Switzerland), where Rhizotech mats and automated irrigation maintain a stable water supply on 7° and 15° pitched roofs [21]. In the Czech Republic, the LIKO-S headquarters features a 350 m² wetland roof and façade treating operational greywater, with reuse for on-site irrigation and building cooling.
In Slovakia, three wetland roof elements were built as part of the greenIZOLA retrofit of an administrative building, combining water retention with biodiversity support on multiple terraces [22,23].
Experimental and research installations further expand the evidence base. At the Helmholtz Centre for Environmental Research (Germany), a pilot wetland roof confirmed effective greywater purification, while a subsequent multi-section research roof established in 2019 examines retention processes, cooling performance and the influence of different growing media under controlled long-term monitoring [9,10,25]. In Korea, a 2×2 m pilot wetland roof demonstrated strong temperature stabilization and vegetation resilience [12]. Several Vietnamese studies investigated greywater treatment under different loading regimes and

plant/media combinations, achieving high removal efficiencies [13–15]. A hydroponic green roof study in Taiwan identified optimal water levels for cooling and temperature stabilization [24]. Hybrid wetland–green roof systems in the Czech Republic showed promising results in combining water treatment and rooftop vegetation growth [26]. A large-scale 3,400 m² wetland roof in Warsaw demonstrated effective stormwater retention and pollutant reduction [19]. Local measurements in Košice (Slovakia) confirmed lower temperature fluctuations on wetland roofs compared to extensive green roofs during dry summer periods [18,27].
These diverse examples collectively demonstrate that wetland roofs are functionally reliable, adaptable to different climates and roof geometries, and capable of providing multiple ecosystem services, including cooling, stormwater retention, nutrient removal and biodiversity enhancement.

4 Discussion

Despite the demonstrated benefits of wetland roofs, certain knowledge gaps persist, necessitating further scientific research and development. Future research is crucial not only for progressively improving existing solutions but also for establishing comprehensive design guidelines, performance standards, and maintenance protocols.
A significant research need is to determine the maximum duration of dry periods during which wetland roof systems can retain their regenerative capacity and functional recovery. This knowledge is fundamental for ensuring system robustness under changing climatic conditions.
In the context of water reuse applications, future research should focus on evaluating the necessity and effectiveness of supplementary water treatment technologies (e.g., UV disinfection), particularly concerning adherence to stringent local water discharge standards.
Simultaneously, continued research is warranted to optimize the selection of plant species to enhance the efficiency of nutrient and contaminant removal from influent waters. Combining various vegetation types could contribute to higher evapotranspiration throughout the growing season.
Further research is also needed in the area of utilizing natural and economically viable materials (e.g., bamboo, coconut) in the construction of wetland roofs designed for greywater treatment.
A comparative analysis of different wetland roof structural designs and their performance across diverse climatic conditions (with an emphasis on local research) is essential.
Long-term, in-situ monitoring of wetland roof operation will enable data collection that accurately reflects their behaviour under the influence of variable external factors such as temperature, solar radiation, precipitation, wind, and humidity. This data can subsequently be used for the calibration and validation of simulation tools and models that predict the behaviour of wetland systems in real-world conditions.

5 Limitations

Wetland roofs represent a developing and highly specific ecotechnology, resulting in a limited pool of peer-reviewed studies available for systematic comparison. The existing research varies widely in methodological approaches, climatic conditions and system configurations, which restricts the possibility of forming standardized analytical models. These limitations should be considered when interpreting the findings of this review.

6 Conclusion

Wetland roofs represent a multifunctional blue-green technology that integrates water management, thermal regulation, ecological benefits and, in some cases, greywater treatment within a single rooftop system. The reviewed studies consistently demonstrate their higher evapotranspiration rates, faster vegetation establishment, improved cooling performance and enhanced biodiversity compared to conventional extensive green roofs. At the same time, practical barriers remain, including structural load requirements, the need for active water management and limited professional awareness.

Despite the relatively small number of existing installations, long-term case studies confirm that wetland roofs can operate reliably and contribute to improved urban resilience. Their potential for decentralized water treatment and climate adaptation highlights their relevance in future sustainable building design. Continued research is essential to develop standardized design guidelines, verify long-term performance under different climatic conditions and support wider implementation.

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