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Review

A Nature-Inspired Green–Blue Solution: Incorporating a Fog Harvesting Technique into Urban Green Wall Design

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Abstract: This research aims to explore the use of vegetation and nets to collect water from fog on facades to meet the needs of buildings' functional requirements, particularly outdoor thermal comfort, water demands, and encouraging sustainability by suggesting a new architectural green–blue wall system. The system is posited to be applicable within an urban context, given its minimal spatial requirements and adaptability to existing structures. However, similar challenges to those encountered by green walls are anticipated, wherein the provision of sustainable benefits is offset by the demands of maintenance and associated additional costs. For this reason, this paper is mainly divided into two parts: in the first part, green facades are explained, referring to their effect on urban environment, including thermal comfort, pollution absorption, noise pollution, and well-being, as well as types of plants to apply on green walls; the second part focuses on the fog collector as an irrigation system for green walls, analyzing its components, structure, and fabric, to identify its development margins in the construction industry. Fog harvesting initiatives predominantly focus on rural regions to cater to agricultural demands; however, limiting fog harvesting to agricultural settings is considered insufficient, as it represents a crucial solution for addressing water challenges in specific urban environments. Nevertheless, it is worth investigating the fog collector's potential for integrating water supply in urban environments as well. The study focuses on exploring the environmental benefits of fog harvesting and green walls, particularly through their combined implementation. The proposed review is significant for guiding the integration of a device into green facades, ensuring water self-sufficiency while concurrently addressing air purification, noise reduction, and thermal comfort for pedestrians and urban inhabitants. Nevertheless, it is worth investigating the fog collector's potential for integrating water supply in urban environments as well. The proposed review is, therefore, useful for integrating a device represented by the fog harvesting system, also identified in the text as the blue system, into the design of green facades, identified in the text as the green system, integrating the blue element in the design of the green wall to make them water self-sufficient and at the same time purifying the air, reducing noise pollution, or giving thermal comfort to pedestrians and inhabitants of the urban context.

Keywords: green walls; air pollution; noise pollution; thermal comfort; well-being; fog harvesting; sustainable façade

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1. Introduction

In recent years, the crisis of resources has been evident, and water is one of them. Water is considered a renewable resource, because it returns to earth through a cyclical process, the water cycle, in the form of rain or snow. Nevertheless, we are witnessing a widespread water crisis. This is due to many factors: population growth coupled with the development of unsustainable habits are dissipating the planet's resources, changing its climate and damaging its natural ecosystem. One of the serious consequences of climate change is the decrease in fresh water. In this scenario, the demand for fresh water is increasing, this leads to the depletion of conventional water basins, such as rivers, lakes, and aquifers. Pollution, in addition to causing various ecological problems regarding ecosystems and health, also makes it difficult to use certain water resources because of their high levels of toxicity [1]. It is important to point out that only a small amount of water on our planet is available as a freshwater reserve [2]. This water is not equally distributed. The utilization of traditional water resources involves an extensive distribution infrastructure characterized by substantial energy consumption and associated expenses. The emergence of water scarcity, exacerbated by climate change, is delineated as a profound consequence, with water being identified as the "Blue Gold" of the 21st century. Given these conditions, fog emerges as a feasible alternative water source. Numerous regions experience the occurrence of fog, and within such environments, fog collectors have been devised to extract water from the moist air mass. Fog harvesting is a passive system, and it relieves the stress upon fresh-water resources. The basic idea of fog harvesting is that when warm, damp air touches a colder surface, the water vapor in the air turns into tiny water droplets and sticks to that surface. In fog harvesting devices, they often use structures like mesh nets or screens with a large surface area. These structures are placed in areas where there is a lot of fog. As the foggy air goes through the mesh, the water vapor in the air turns into droplets on the mesh because of the temperature difference. These droplets gather and move down the mesh, finally collecting in a container at the bottom. Presently, fog collectors represent low-technology apparatus, and initiatives focusing on fog harvesting are frequently undertaken in arid regions with the aim of addressing agricultural and reforestation needs [3,4].

Water's ability to capture pollutants in the air [5] and the air-purifying attributes of green vegetation constitute additional advantages conferred by the implementation of systems aimed at advancing the United Nations Sustainable Development Goals (SDGs) [6–16]. By integrating fog harvesting technology into green wall systems, the overall sustainability of these structures is enhanced. This approach contributes to environmental conservation by utilizing a renewable water resource and mitigates the environmental impact associated with traditional irrigation methods. Additionally, it reinforces the ecological benefits of green walls, such as air purification and thermal regulation, making them more resilient and self-sufficient in terms of water needs.

Several studies conclude that there is a strong relationship between sustainable development and occupational health, and for this, the sustainability of the environment must be considered [17]. As per the World Health Organization (WHO) ambient (outdoor) air pollution report for the year 2019, 99% of the global population resided in locations where the air quality standards set by the World Health Organization were not in compliance. The combined effects of outdoor ambient air pollution and household air pollution have resulted in an annual toll of 6.7 million premature deaths [18]. Furthermore, ambient air pollution alone was estimated to have caused 4.2 million premature deaths worldwide in 2019, with 89% of those occurring in low- and middle-income countries, particularly in South-East Asia and the Western Pacific Regions.

This paper aims to demonstrate the explorations of design criteria to develop a novel concept of a green smart water collector with the objective of striking a balance that optimizes the coexistence of fog harvesting systems and green wall vegetation while capitalizing on their respective environmental contributions. It aims to reach a design that harmonizes the implementation of fog harvesting within green walls, despite their historically separate deployment. Leveraging its vertical development, this textile structure has the potential for integration into building facades, complementing a green wall design to enhance the resilience of constructions. By combining the characteristics of both systems (green and blue), a shading effect can be facilitated, along with various environmental advantages.

These include diminished reliance on cooling systems, reduced energy demands, and consequently, a lowered ecological footprint [19–22]. Based on the liquid water content of the fog, the gathered water can find application in irrigating green roofs/walls, gardens, or ideally, serving domestic purposes [23]. The analysis of local weather data plays a pivotal role in expanding the applicability of this system to different regions. However, of greater significance is the imperative to enhance the technological aspects of the device to enable its implementation in novel application domains [24].

It is crucial to acknowledge that while the device is designed to integrate two systems to complement each other, it also amplifies the challenges faced by each system individually. This includes considerations such as maintenance costs and the application challenges associated with novel environmental solutions where further experimental work is needed.

2. Green Walls System

2.1. Green Wall Systems

The green wall approach is based on the idea of taking advantage of the ability of some plants to grow on the vertical surfaces of buildings. Two prominent categories of green walls are recognized: green facades, characterized by walls adorned with climbing plants like Boston Ivy or English Ivy, and living wall systems that provide the possibility of using other plants on vertical surfaces which is considered a more modern approach to green walls [25].

2.1.1. Green Facades

Green facades encompass the deployment of climbing vegetation, which can be attached to a building facade either directly or indirectly with the aid of a supporting structure. Green facades can be delineated into two distinct categories. The plants are either directly planted in the soil or planted in boxes to cover higher altitudes, see Figure 1. According to [26] in this scenario, two categories of plants are discernible: the first is those that adhere directly to a wall surface, with or without human intervention with no need for a watering system and the possibility of using manual watering. This type of wall could pose a threat to the wall structure if it is not controlled [27]. The other type of plant is the plant species with no adhesive roots to enable them to grow on the facade of a building so they require a supporting structure. This type of wall provides the advantage of having insulation between the green facade structure and the building facade. Manual watering is also possible for small to medium-size walls, but automated watering systems are preferred for larger walls.

2.1.2. Living Walls System

Living wall systems represent a sophisticated iteration within the realm of greening systems, predominantly composed of modular panels housing soils or artificial growing mediums, hosting various plant types beyond climbers. These encompass species like shrubs, ferns, and groundcovers. Categorically, living wall systems can be classified into two discrete groups: continuous systems and modular systems.

A continuous living wall system, colloquially referred to as a vertical garden, is predicated on the utilization of a fabric layer functioning as a substrate for plant root development. This system employs hydroponic methodologies to facilitate nutrient absorption by the plants through irrigated water. Generally, the fabric layer is interlinked with waterproof membrane layers and securely affixed to a supporting framework, see Figure 2.

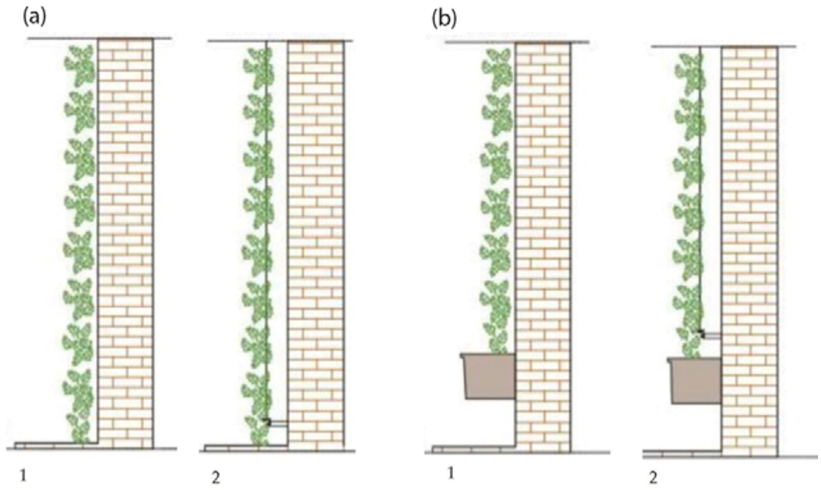

Figure 1. (**a**) Utilization of self-climbing plant species (1) in direct contact with the wall (2) supported by a dedicated structure for the implementation of a green façade. (**b**) Green façade using plants rooted in the box (1) planter box at the bottom with plants directly on the wall, (2) planter box at the bottom with plants on supporting structure. Source: [28].

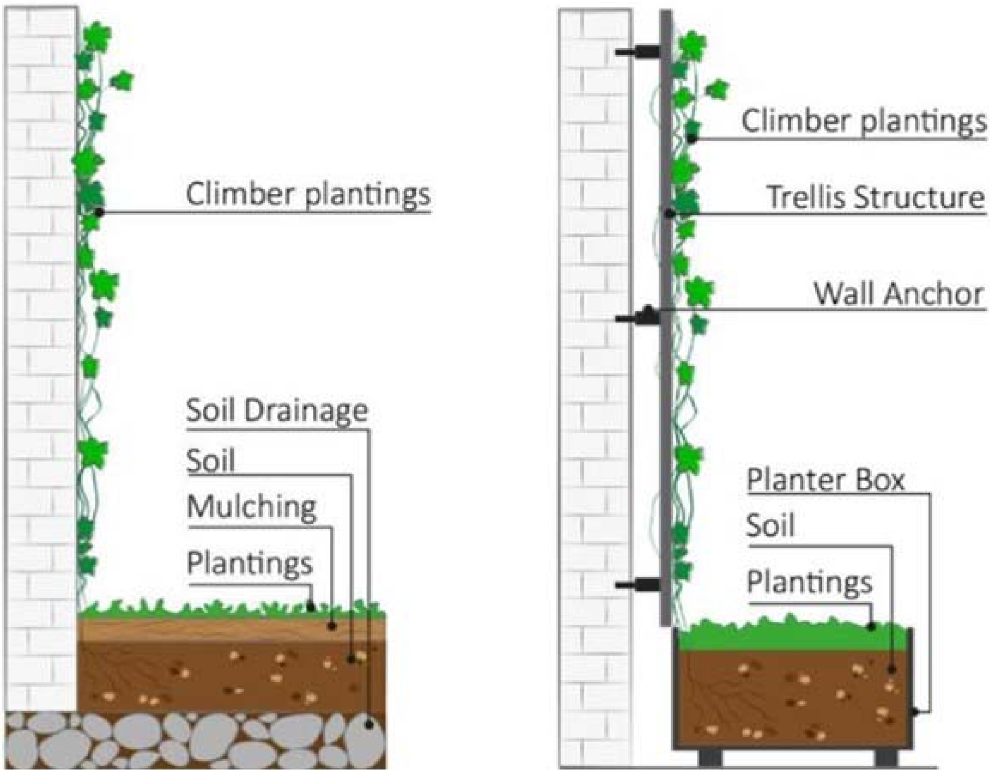

Figure 2. Continues living wall systems. Source: [29].

A modular living wall system comprises pre-vegetated panels that are affixed to a structural wall. These modular panels may be installed vertically or at an angle, with a substrate compressed within the horizontal panels to accommodate the growth of the planted species. Typically, an irrigation system is situated between the panels, facilitating water drainage throughout the entire facade, ultimately collected at the bottom through gravitational forces [30]. This system offers the advantage of providing additional planting depth and facilitating the replacement of deceased plants compared to the continuous system, see Figure 3.

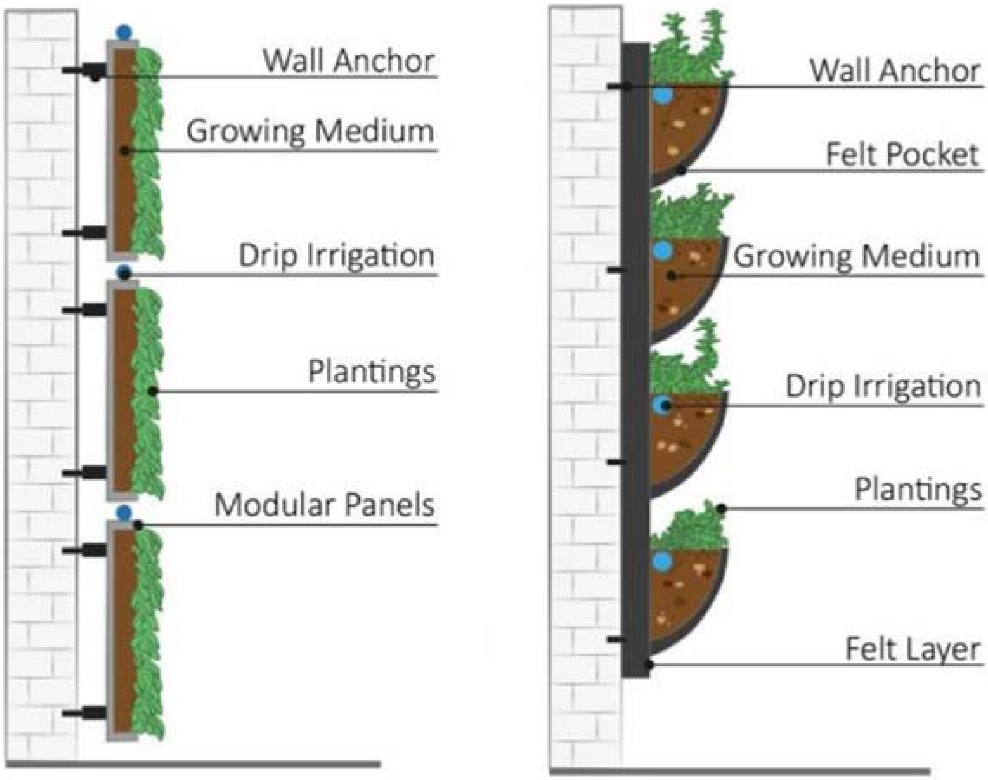

Figure 3. Modular living wall systems, source: [29].

2.2. Vertical Vegetation Effect on the Environment

Recognizing the advantages associated with incorporating vertical vegetation on building exteriors is essential [31]. The primary emphasis will be on the benefits elucidated by studies on green walls, particularly in relation to thermal insulation, mitigation of air and noise pollution, and enhancement of well-being when employed on the exterior surfaces of buildings.

2.2.1. Green Walls and Thermal Comfort

Green walls or greenery systems [32–34] offer multifaceted thermal advantages encompassing evapotranspiration, thermal insulation, shading, and enhancement of thermal comfort. Additionally, these systems provide evaporative cooling to mitigate cooling requirements and minimize wind-induced convection losses [35,36]. During summer, the green system can obstruct direct sunlight, inducing a cooling effect and diminishing energy consumption for air conditioning. Conversely, in winter, the system impedes heat dissipation from the interior of the building [37].

Eumorfopoulou and Kontoleon [38] conducted an experimental investigation aimed at assessing the thermal impact of plant-covered walls on building envelopes. The study focused on a traditional green façade (*Parthenocissus tricuspidata*) with a thickness of 25 cm, situated on an east-facing orientation in Thessaloniki, Greece. The building had heat-insulated brick façade walls. Various parameters, including exterior and interior surface temperatures, foliage temperature, and environmental temperatures, were recorded during the investigation. The study also involved theoretical heat flow calculations through the wall. The findings revealed that the presence of green coverage resulted in a maximum daily temperature reduction of approximately 5.7 °C on the exterior surface and 0.9 °C on the interior surface of the east-facing building wall. This reduction translated to a 0.5 °C decrease in indoor temperature compared to the external temperature with green cover, while it was 0.4 °C for the bare wall.

The findings of the literature survey clearly show that green roofs and facades are important options for mitigating building-related energy consumption, such as energy savings in buildings [37,39]. Greenery systems can also provide thermally comfortable indoor and outdoor conditions, with a yearly average CO_2 accumulation of 13.41–97.03 kg carbon/m^2 for 98 m^2 of the vertical greenery system [40]. Green roofs and facades were identified as one of the most acceptable sustainable solutions to urban heat island-related challenges based on the thermal efficiency of buildings and microclimatic conditions of indoor and outdoor environments [32,35].

The quality of indoor–outdoor environments faces challenges due to localized and transient issues such as overheating, elevated air pollution levels, and extensive impervious surfaces, thereby diminishing the resilience of urban spaces to climate change-induced threats. In light of this, the current research centers on assessing a greenery system aimed at enhancing outdoor thermal conditions and alleviating local heat exposure for pedestrians in the continental Mediterranean setting [41]. The method enables local warming mitigation for pedestrians outside by promoting "alive" shading systems to be used in open public places, resulting in physical and societal benefits [42,43].

2.2.2. Green Walls and Air Pollution Abatement

Concerning the reduction in air pollution facilitated by green walls, a study conducted by M. Köhler proposed that the implementation of green facades on all feasible surfaces could capture approximately 4% of the annual dust-fall in an urban area [44]. As an illustration, Boston Ivy (*Parthenocissus tricuspidata*) may function as a metal-capturing agent for a diverse array of metals (aluminum, cadmium, cobalt, chromium, copper, iron, nickel, lead) present in the atmosphere as particulate matter [45]. An additional investigation conducted by Sternberg demonstrated that English Ivy facades on certain historical structures in Oxford functioned as efficient particle traps, displaying a potential dust absorption rate of 2.9×10^{10} particles per m^2 for the upper side of the leaves. Consequently, Ivy was acknowledged for its value in safeguarding historical buildings against air pollution [14].

To assess the particulate deposition characteristics of Ivy, an investigation was conducted in the vicinity of Bergen op Zoom in the Netherlands. The study involved collaboration between Ivy situated on a sound barrier adjacent to a busy street and naturally growing Ivy on a tree in a woodland. The findings revealed higher particle loads on the Ivy located near the busy road (1.47×10^{10} particles per m^2) compared to the woodland Ivy (8.72×10^9 particles per m^2). However, the results also indicated that the upper side of the leaves captured particles twice as effectively as the underside. The study demonstrated that English Ivy exhibits superior performance in particle absorption compared to surfaces made of painted metal, aluminum, glass, and paper [10].

The study of [11] explores the effectiveness of an active green wall biofilter in mitigating urban pollution resulting from the Black Summer wildfire in Australia during 2019–2020. The primary aim of the research was to evaluate the capacity of the biofilter to purify wildfire-polluted ambient air by removing NO_2, O_3, and $PM_{2.5}$, thereby providing clean air during wildfire events. The study also examined the impact of ambient pollutant concentrations on the filtration efficiency of the biofilter during such events. Four local species were tested, namely, *Westringia fruticosa* (coastal rosemary), *Myoporum parvifolium* (dwarf native myrtle), *Stobilanthes anisophyllus* (goldfussia), and *Nandina domestica* (heavenly bamboo). The results revealed that the green walls were effective in filtering the air during high levels of pollution resulting from wildfire events, in which NO_2 was removed with higher efficiency than O_3 and $PM_{2.5}$.

Furthermore, in a study performed by [9], different tests were carried out for 13 days to study the process of capturing air pollutants with an equivalent diameter greater than 8 μm (PM_8) in Braga and Guimarães in Portugal. The collection locations were near busy streets and included testing the ability of different types of plants to capture pollution in the air. Three species of plants were tested, *Quercus palustris* Muenchh, *Hedera helix,* and *Parthenocissus quinquefólia*. Four sampling sites were selected and the capacity for capturing PMs by the plant leaf surfaces was calculated. The final results proved that *Hedera helix* (in both cities) was able to capture air pollutants faster than the other tested species, as the

Hedera Helix species had a total specific removal value of 674.24 mg/m^2 in Braga and a total specific removal value of 760.56 mg/m^2 in Guimarães.

More recently, [7] conducted a study aimed at evaluating the ability of different plant species to capture particulate matter (PM) in a green wall structure. The study had three main objectives: (1) to assess the capacity of the selected plant species to capture PM using scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) analysis, (2) to determine the accumulation of heavy metals on their leaves, and (3) to estimate the tolerance level of plant species for air pollution using the anticipated performance index (API) and to identify the most resistant species based on the results obtained. The study investigated the growth of nine plant species near a busy road in Mashhad, Iran. The results indicated that *Carpobrotus edulis* and *Rosmarinus officinalis* were the most tolerant to air pollution, while *Kennedia prostrata* was the least tolerant. All the plant species trapped suspended particles on their leaves, with some species showing high levels of carbon and oxygen in the deposited particles, indicating that the particles originated from dust. *Sedum reflexum* accumulated the highest levels of Cr, Fe, Pb, and As, while *Malephora crocea* showed the greatest increase in heavy metal concentration. The study concluded that *Carpobrotus edulis* is the most suitable plant species for planting in air-polluted areas of the city, followed by *Lavandula angustifolia* and *Rosmarinus officinalis*.

It must be noted that, in relation to the vegetation in the street canyon, the heterogeneity of urban morphology causes complex flow patterns due to the interactions between the atmosphere and urban features, such as buildings and vegetation. This results in reduced street ventilation, which, when coupled with significant pollutant emissions from vehicles, leads to elevated concentrations of pollutants (such as NO_2, PM_{10}, $PM_{2.5}$) and steep concentration gradients within streets [46]. Studies have shown that green walls (GW) do not disrupt the pre-existing airflow patterns within street canyons, unlike trees and hedges which have been found to obstruct natural ventilation [6,8,15].

2.2.3. Green Walls and Noise Pollution Abatement

According to [47], the majority of greenery systems exhibit notable sound absorption capabilities, with an average absorption rate of approximately 41% in the 800 Hz frequency range. Additionally, these systems demonstrate sound reduction levels ranging from 4 to 9.9 decibels for frequencies in the low to middle range. On the other hand, within the framework of the EU-funded SILENTVEG initiative, an investigation was conducted into the absorptive characteristics and obstructive capabilities of the living wall arrangement, enveloped by *Helichrysum thianschanicum*. The findings indicated that the living wall system effectively lowered the noise level to an average of 15 dB, demonstrating a 'sound absorption coefficient' of 0.40, signifying a 40% absorption of sound [48].

Furthermore, according to [48], when comparing green walls to common structural wall materials in terms of noise reduction, the impact of green walls on the indoor acoustic environment may not be considered significant. For instance, the noise reduction provided by brick walls can range from 30 dB in low frequency up to over 50 dB in high frequency due to their reflective properties. However, with regard to the noise absorption capabilities of green walls, it has been found that they generally exhibit better sound absorption characteristics than many structural materials, particularly at lower frequencies. Although they may not compete with materials like fiberglass board at high frequencies, green walls still demonstrate good performance in this regard, thus making it a good option to have in street canyons that suffer from high levels of traffic and noise.

In order to illustrate the impact of green envelopes, a simulation study was executed to examine the potential mitigating influence of a green building envelope on the surrounding urban environment. The investigation was conducted within enclosed courtyards shielded from the road by buildings, positioned centrally among six-story tower blocks, and each courtyard separated by crossroads. The analysis focused solely on the noise emanating from the busy road as the source. The results revealed that green roofs exhibit a more substantial reduction in noise levels, presenting a potential decrease of up to 7.5 dB. Conversely, the reduction afforded by green walls is comparatively smaller and contingent on the material used for the facade of the building facing the street [49].

The study of [50] investigated the impact of green foliage on noise pollution. Different locations were analyzed, and measurements were taken at each site during two distinct phases: prior to the onset of leaf emergence (referred to as "before leaf emergence" or BLE) and subsequent to full leaf development (referred to as "after leaf emergence" or ALE). The findings obtained from this study lend credence to the fact that the presence of foliage leads to a reduction in ambient noise levels.

2.2.4. Green Walls and Well-Being and Mental Health

As previously mentioned, green walls have the potential to enhance the quality of life in urban areas by reducing air and noise pollution and improving thermal conditions. Nevertheless, the advantages of green walls extend beyond the physical realm, as they can also contribute positively to the psychological well-being of the general population. The research conducted by [51] involved data collection and analysis to explore the effects of indoor plants, interior green walls, and natural views on anxiety, stress, mood, and overall well-being among elementary school students in London. It was found that the inclusion of natural elements leads to an immediate decrease in levels of stress and anxiety, as well as an increase in overall well-being and positive mood. Notably, exposure to window views and indoor plants were observed to have the most positive impact on stress and anxiety levels. However, the positive effects on mood and well-being were observed to decline after a period of 2 to 5 weeks of exposure to natural elements.

Another study examined the impact of green walls featuring live plants on the attention and classroom perceptions of elementary school students. Four classrooms were used to compare the students' performance on attention tests and classroom evaluations with and without a green wall. The results, adjusted for baseline scores, demonstrated that students in classrooms with green walls outperformed their peers on attention tests and provided more favorable classroom ratings. Most students expressed a positive view of the green wall and believed that it had a beneficial impact on their classroom [52].

One study explored the attitude that society might have in regards to the application of vertical greening system on the facades of buildings, and it was found that people mostly had a positive attitude towards the application of green walls on building surfaces in the city [53]. Another study evaluated the benefits derived from the publicity surrounding the installation of a living wall in the 'Quirónsalud Sagrado Corazón' Hospital in Seville, Spain, and assessed the perception of the general public towards it. The results showed that although some participants in the study did not give much importance to gardening, the majority reported experiencing positive emotions and reactions when in the presence of vegetation. Many participants were not previously familiar with living walls (LWs), but upon encountering them, most believed that these elements have a positive effect on psychological well-being and contribute to the recovery of those who perceive them. Furthermore, most participants in the study agreed with the investment made by the hospital in the LW and preferred it over other options, both green and non-green. They would even choose a hospital with more vegetation over a similar one without plants [54].

Thus, it is safe to say that the psychological benefits derived from green walls, including advancements in well-being, stress reduction, and augmented mental health, demonstrate intricate interconnections with the favourable environmental impacts associated with these installations. This nexus involves enhancements in air quality, regulation of temperature, and noise abatement among the urban fabric. This dual enhancement contributes significantly to fostering overall well-being and advancing the sustainability of urban communities. The integration of green walls into urban landscapes thus emerges as a pivotal strategy for promoting a harmonious and healthful urban environment.

2.3. Green Walls Maintenance

Regarding maintenance, green walls normally depend on vines that grow either from the soil or from a planting box, and each location and type of plants requires a different system and different irrigation method. For instance, in certain geographical locations, the selection of plants might include non-self-sustaining vine species, necessitating increased attention and care. Conversely, some plant species could be deciduous, while others yield flowers and fruits, implying the need for specific attention and maintenance. However, diligent and sustained maintenance of most plants will yield substantial benefits over the long term. It is essential to acknowledge that, in instances where a supporting structure is required, meticulous consideration should be given to ensure the proper installation of cables, thereby promoting the mature growth of plants. Moreover, green facades, owing to their dependence on living species, cannot guarantee predetermined outcomes and are subject to a level of unpredictability beyond complete control. Consequently, skilled labor, elevated costs, and ongoing efforts are necessary to ensure the security and maintenance of supporting structures.

Regarding the expenses associated with the supporting system, the green facade presents a cost-effective solution when compared to alternative techniques like the living wall system. The latter typically requires a greater quantity of materials, intricate designs, complex irrigation systems, and increased maintenance efforts [55].

It is imperative to highlight that in addition to maintenance challenges, architectural integration introduces an additional stratum of complexity, necessitating meticulous consideration of elements such as the provision of structural support, establishment of irrigation systems, and compatibility with existing building materials. The effective resolution of these challenges mandates a comprehensive approach aimed at augmenting the practicality and promoting the widespread adoption of green walls across diverse architectural settings.

2.4. Plants for Green Walls Application

According to [31], the environmental advantages and health implications linked to vertical green systems (VGS) are contingent upon a multifaceted array of variables. The judicious choice of plant species plays a pivotal role in optimizing the efficacy of VGS in enhancing thermal comfort, mitigating noise levels, and mitigating air pollutants. Essential considerations in the selection of plant species encompass attributes such as size, growth patterns, leaf morphology, texture, and deciduousness, among others. These considerations should be carefully weighed based on the intended effects and local conditions, including facade orientation, wall types, building height, and water requirements.

The investigation carried out by [56] examined the viability of using local plant species that thrive on old roofs and walls in the Lisbon region for green roofs, and assessed their response to different irrigation levels. The study found that using native plant species that naturally grow in rock fissures of urban structures like walls, roofs, and roads for extensive green roofs can be an effective way to conserve native plants and prevent biodiversity loss in urban ecosystems. Using native species requires less maintenance than exotic species, and they are well adapted to the harsh conditions of urban environments, especially in Mediterranean climates with drought, intense sunlight, and high temperatures. Also, between the four species studied, Antirrhinum Linkianum demonstrated good flower and seed production and green coverage under 60% ETo conditions. Additionally, no significant differences were observed between irrigation levels of 60% ETo and 100% ETo.

Thus, in addition to choosing plants based on the desired effect and local conditions, the ecological considerations for green walls must be taken into consideration which involves a thoughtful selection process that prioritizes native species, supports local wildlife, avoids invasive plants, considers water efficiency, promotes soil health, and adapts to seasonal changes.

This study highlights the significance of employing the aforementioned approaches in the process of selecting plant species for implementation in green walls.

3. Blue System

Global water distribution is not uniform, a consequence of both natural climatic conditions and excessive exploitation for anthropogenic purposes [57]. Despite water encompassing nearly three-quarters of the Earth's surface, the majority, approximately 97.4%, is saline water. Conversely, the portion of freshwater suitable for human consumption amounts to a mere 2.5% [2]. Nevertheless, the distribution and consumption of water are not uniform, with per capita consumption being directly impacted by water availability. Indeed, inadequate water management often underlies numerous hydrological challenges [58] and is frequently compromised by contamination [1]. The primary sources of freshwater are derived from surface waters and subterranean reservoirs. In order to utilize this water, extraction is necessary, followed by treatment. Subsequently, a distribution system is required, the operation of which is contingent upon the availability of energy [59]. Although water is categorized as a renewable resource, the current rates of consumption are insufficient to sustain its availability. In addition to the existing constraints on water resources, the global population is anticipated to increase. Consequently, the projection by UNESCO indicates an expected 55% rise in water demand [60]. In accordance with the World Resources Institute (WRI), approximately 25 nations globally experience severe water stress on an annual basis. Regions experiencing significant impact include areas like the Middle East and North Africa, where 83% of the populace encounters annual exposure to exceptionally high water-stress, and South Asia, where this proportion stands at 74% [61]. Regarding pollution, fog cleanses the air effectively due to water's ability to capture particulate matter. However, at the same time, chemicals and compounds that pollute the air can fall with fog to pollute soil and surface waters, affecting the surrounding environment [5]. Under normal atmospheric conditions, water particles mix with various gases, including carbon dioxide, sulfur dioxide, and nitrogen oxides. Elevated concentrations of air pollutants can thus cause water vapor in the air to react with these gases and become even more acidic. Precipitation serves as a potent mechanism to eliminate atmospheric pollutants from the air. However, in this case, falling water would be polluted, which could pose some harmful effects if the collected water was used for consuming purposes or deposed into the ground, affecting plants and animals [5,62].

3.1. Alternative Water Source

In a context marked by an increase in water demand alongside a decrease in water supply, fog presents itself as a potential supplementary water reservoir. The objective is to discern opportunities for enhancement and evaluate the potential for positively influencing urban water resource management. A new water resource is needed, and fog water collection represents a promising yet relatively unexplored potentiality; exploiting fog water could help achieve the sustainable development goals [63].

Fog represents a meteorological occurrence delineated by the suspension of minute aqueous droplets within the atmosphere. Physically, the generation of fog occurs when a saturated air mass reaches its dew point [64]. The classification of fog is contingent upon its genesis mechanism, which includes radiative heat dissipation, the mixing of two parcels of saturated air initially at different temperatures, and upward displacement followed by the subsequent cooling of an air parcel. [65]. The fog phenomenon impacts numerous regions globally, with some of these areas situated in arid climates, while others are located in territories expected to confront water scarcity in the forthcoming years.

Fog Collection System

Throughout history, human populations residing in arid fog oases have adapted to the challenging environmental conditions, leading to the development of fog collection systems. Notably, certain fog harvesting projects have been geographically documented. The practice of collecting fog water has demonstrated a notable increase over time, with noteworthy instances observed globally, particularly in regions such as the Canary Islands, Chile, Colombia, Eritrea, Ethiopia, Guatemala, Israel, Morocco, Namibia, Oman, Peru, and

South Africa [66]. With a variety of locations, fog water collection rates exhibit substantial variability, with operational projects commonly experiencing yearly averages ranging from 3 to 10 L per square meter of mesh per day [67].

The effectiveness of collecting mist water depends on several external factors, such as the average droplet diameter (MVD), as well as the liquid water content (LWC); they also depend on wind speed and presumably on relative humidity and temperature [68,69]. Other factors that determine collection efficiency are associated with the device itself; therefore, these factors are related to the mesh and structure design [67]. The water collection system is passive and is activated when a wet air mass is pushed by the wind through the system's fabric. Hence, the droplets present in the air adhere to the filaments of the fabric, coalesce, and when they attain a specific size and weight, they flow on the surface of the fabric by gravity, are collected from a channel and then stored in a deposit. The fog collector consists of a mesh and a support structure [70].

In recent years, various fog harvesting techniques have been successfully implemented worldwide with a sharp increase in research into technological developments in mist collection systems and experimental campaigns analyzing the system, testing different configurations of the structure and different types of mesh [23,24,66,67,71–73].

The most commonly used fog collector is the large fog collector (LFC), described specifically by [72]. It is a two-dimensional tensile structure, consisting of two poles and tensors to which a 40 m^2 screen of fabric, the Raschel mesh, is attached and is shown in Figure 4.

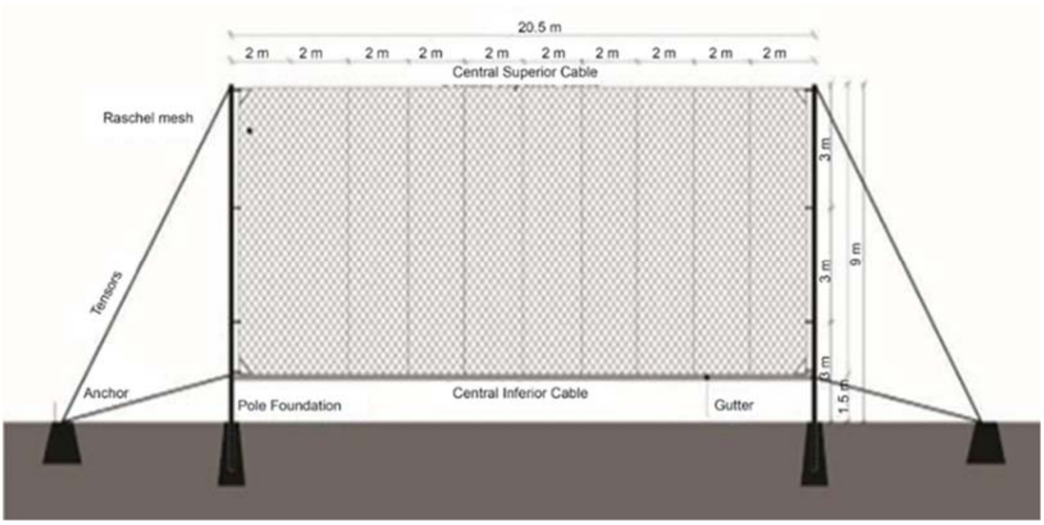

Figure 4. Large fog collector. Edited by the author: M.G. Di Bitonto.

The Raschel mesh is a very common fabric used in many areas: in agriculture as a shading net, in the field of construction for scaffolding, and in packaging. It is a woven mesh mostly comprising large flat fibers, knitted to form triangular openings [67,74].

3.2. Fog Harvesting in Building Facades

The initiation of a fog harvesting project requires a thorough analysis of a site's climatic conditions. Critical factors influencing the placement and dimensions of the fog collector encompass parameters such as wind speed, wind direction, mean humidity, temperature, and liquid water content (LWC) [75]. In fact, the collectors should be oriented perpendicularly towards the main wind direction, and generally, more wind speed implies more water collection [72]. Considering the vertical development and lightweight nature of the traditional fog collector, there is contemplation regarding the integration of this device into a smart membrane facade [76]. For this integration to be feasible, the fog collector's structure needs to be designed to harmonize with building architecture. Additionally, the sizing of the novel fog collector should align with the water demand of the respective building. The initial step involves conducting a test campaign to analyze the fog water potential of the selected area. It is advisable to install at least one standard fog collector (SFC) for an extended period, preferably a year or more, to obtain a seasonal mean collection [72]. After determining the collection capacity, the sustainable facade's dimensions can be tailored to meet the water requirements of the building. Additionally, considering that the primary wind direction may change throughout the year, the facade should be adaptable to diverse conditions to ensure the proper functioning of the fog harvesting system [24,72,73]. Consequently, flexibility becomes a crucial aspect in the development of sustainable facades, and the collected water can be employed for irrigating a green facade [23]. The volume of fog water collected is subject to variation across different locations, influenced by factors such as seasonal variations and the specific structure and mesh employed in the fog collector. Due to this, the green system design should be conceived together with the water collection results [67].

Moreover, it is customary to posit that the incorporation of such a structure into building facades necessitates distinct considerations compared to the application of a standard fog harvesting structure. These considerations encompass factors like structural load-bearing capacity, material compatibility, aesthetic integration with the building's design, provisions for maintenance, and water treatment to ensure quality, among other aspects.

3.3. Blue System Maintenance

According to [77], the preservation of a fog harvesting system necessitates ongoing observation, routine tightening of support cables and mesh, swift rectification of any minor tears, and realignment or modification of collection troughs. This imposes supplementary labour and exertion on a subsistence community, which may have limited time and energy to allocate. Thus, it is imperative that the maintenance of the system and its components remains feasible within their capacities and aligns with their cultural norms.

In accordance with the ongoing project conducted by L. Hadba and M. G. Di Bitonto, which involves the implementation of a small-scale fog harvesting system in the Mountain of Penha, Guimarães, diligent oversight of the fog harvesting structures is necessary. This includes the periodic assessment and potential adjustment of the mesh, as well as regular cleaning to remove accumulated debris such as fallen leaves that obstruct the drainage of collected water. Furthermore, adjustments to the overall structure and replacement of the utilized water storage units, specifically 5 L water bottles are also required, see Figure 5.

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

Figure 5. Instances where the fog harvesting system necessitates ongoing monitoring include: (**a**) mesh ruptures; (**b**) disconnection between the collector and the collecting tube; (**c**) obstruction of the drainage system caused by the accumulation of leaves. Source: L. Hadba.

4. Combination of Green and Blue System

The symbiosis between green walls and fog harvesting systems is rooted in their reciprocal functions aimed at tackling environmental issues, specifically in regions with water scarcity. Green walls, characterized by vertically aligned vegetation on building exteriors, contribute significantly to energy efficiency, air quality enhancement, and aesthetic augmentation. Conversely, fog harvesting systems specialize in capturing atmospheric moisture to establish a sustainable water source. The integration of these systems establishes a synergistic alliance, fostering mutual benefits. However, this collaboration is not without challenges: encompassing the optimization of water efficiency, structural load-bearing capacity, material compatibility, mangment of the microclimate dynamics, assurance of energy efficiency, attainment of seamless aesthetic integration, reinforcement of environmental resilience, and mitigation of potential environmental impacts must all be considered.

The results from the conducted studies on the types of green walls and possible combination with fog harvesting technology can provide an insight into the environmental sustainability of different combined systems.

Each type of green wall has noticing points. When fog harvesting is used as the main irrigation source, some challenges and requirements need to be followed depending on the characteristics of each type, as follows:

- Green facades implemented directly have demonstrated minimal environmental burden, exhibiting favourable effects on air quality. The calculated payback period for such facades falls within the range of 16 to 24 years [78], considering their noteworthy energy-saving attributes. This form of greening can be regarded as both sustainable and easily implementable. Nonetheless, it is essential to consider the potential detrimental effects resulting from the direct impact of planting on the structural integrity of the wall.

When a fog harvesting system is added to this type of green wall, an exterior structure is needed to support the water-collecting mesh, as this green system is not based on any structure. Thus, the application of the blue system requires the design and application of an added structural layer to the façade, together with water storage and distribution to the plants.

- The indirect green facades showed some environmental burden; however, they presented comparable advantages in terms of energy conservation and enhancement of air quality when compared to direct facades. The calculated payback period for most cases falls within the range of 16 to 42 years [78]. Moreover, indirect green facades could be regarded as a viable sustainable solution.

The fog harvesting system can be applied to an indirect green façade using two methods: it could be carried out either by adding the blue system to the same supporting structure of the green wall, or by installing an independent structure in front of the green wall. In the second case, the irrigation system should be developed, connecting the water collected from one supporting structure to the other.

- The living wall system (LWS) demonstrated the most substantial environmental burden, primarily attributable to the materials used and durability considerations. Additionally, the LWS emerged as the costliest system under scrutiny, with significant installation expenses associated with pre-vegetated panels, coupled with ongoing maintenance costs involving panel replacements, plant species oversight, and the upkeep of the irrigation system. Nonetheless, it presents superior environmental solutions owing to the diverse range of plant options it offers in comparison to green facades.

In this case, adding the fog harvesting system to the irrigation of plants, both through a hydroponic system or automated watering, implies adding a supporting structure to fog harvesting. The type of the plants used will impact the amount of water needed, as well as the type of LWS.

5. Research Carried Out on Combined Green and Blue Systems: Literature Review

This review intends to analyze the work developed and published in recent years on the use of integrated or combined systems aiming to find solutions that lead to sustainable buildings.

The literature review process was conducted according to the following steps. First, the search was derived from the Scopus database, which has been regularly utilized for conducting reviews and is regarded as a reliable source for searching for scientific articles [31]. Second, the aim of selecting the keywords was to identify that an isolated search of each topic has many outcomes/results but the combined results are very low or non-existent. The selection of keywords was intended to define the main subject and not the outcomes of the main subject results or benefits; therefore, the keyword terms were: [green walls; fog harvesting; water façade; sustainable façade], and not the outcomes or results, such as: [air pollution; noise pollution, thermal comfort, well-being]. Third, the search was carried out between 2018 and 2023 and was restricted to articles, conference papers, and book chapters. The documents are written in English and published in electronic bibliographic databases up to 22 April 2023. Fourth, the search was carried out in all fields but only the following fields were extracted: [Environmental Science, Engineering, Energy, Social Sciences, Agricultural and Biological Sciences, Earth and Planetary Sciences, Computer Science]. Fifth, the search was conducted using two approaches: first, each keyword term has to be in the title; in the second approach, the keyword terms need to be in the abstract. Both approaches are shown in Tables 1 and 2.

Table 1. Document research with keywords in the TITLE.

Document Research with Keywords in the Title between 2018 and 2023 (Without Duplicates)												
Keywords	**"Green Walls"**		**"Fog Harvesting"**		**"Sustainable Façade"**		**"Water Façade"**		**"Living Wall System"**		**"Green Walls" + "Fog Harvesting"**	
	Field	**N°**	**Field**	**N°**	**Multi-Field**	**N°**	**Multi-Field**	**N°**	**Multi-Field**	**N°**	**Multi-Field**	**N°**
Scopus	All fields	214	All fields	91	All fields	32	All fields	31	All fields	31	All fields	0
	Environmental Science	122	Environmental Science	21	Environmental Science	10	Environmental Science	11	Environmental Science	14	Environmental Science	0
	Engineering	86	Engineering	29	Engineering	24	Engineering	15	Engineering	15	Engineering	0
	Social Sciences	48	Social Sciences	2	Social Sciences	5	Social Sciences	6	Social Sciences	6	Social Sciences	0
	Energy	37	Energy	14	Energy	4	Energy	17	Energy	3	Energy	0
	Agricultural and Biological Sciences	30	Agricultural and Biological Sciences	1	Agricultural and Biological Sciences	1	Agricultural and Biological Sciences	0	Agricultural and Biological Sciences	8	Agricultural and Biological Sciences	0
	Earth and Planetary Sciences	20	Earth and Planetary Sciences	3	Earth and Planetary Sciences	0	Earth and Planetary Sciences	3	Earth and Planetary Sciences	0	Earth and Planetary Sciences	0
	Computer Science	16	Computer Science	2	Computer Science	2	Computer Science	1	Computer Science	4	Computer Science	0

Table 2. Document research with keywords in the ABSTRACT.

Document Research with Keywords in the Abstract between 2018 and 2023 (Without Duplicates)												
Keywords	**"Green Walls"**		**"Fog Harvesting"**		**"Sustainable Façade"**		**"Water Façade"**		**"Living Wall System"**		**"Green Walls" + "Fog Harvesting"**	
	Field	**N°**	**Field**	**N°**	**Multi-Field**	**N°**	**Multi-Field**	**N°**	**Multi-Field**	**N°**	**Multi-Field**	**N°**
Scopus	All fields	3842	All fields	329	All fields	553	All fields	586	All fields	512	All fields	1
	Environmental Science	833	Environmental Science	65	Environmental Science	193	Environmental Science	142	Environmental Science	118	Environmental Science	1
	Engineering	1158	Engineering	115	Engineering	338	Engineering	328	Engineering	188	Engineering	0
	Social Sciences	216	Social Sciences	7	Social Sciences	108	Social Sciences	70	Social Sciences	53	Social Sciences	1
	Energy	398	Energy	39	Energy	161	Energy	113	Energy	49	Energy	0
	Agricultural and Biological Sciences	752	Agricultural and Biological Sciences	10	Agricultural and Biological Sciences	17	Agricultural and Biological Sciences	25	Agricultural and Biological Sciences	78	Agricultural and Biological Sciences	1
	Earth and Planetary Sciences	0	Earth and Planetary Sciences	9	Earth and Planetary Sciences	64	Earth and Planetary Sciences	42	Earth and Planetary Sciences	0	Earth and Planetary Sciences	0
	Computer Science	176	Computer Science	61	Computer Science	57	Computer Science	39	Computer Science	65	Computer Science	0

The screening process encompassed assessing the eligibility of retrieved articles. Thorough reviews of titles, abstracts, keywords, and full texts were conducted to identify papers primarily focused on examining the impact of the specified search terms on the design aspects of green facades, water self-sufficient facades, and fog harvesting systems implemented in building structures. Duplicate articles and documents without full texts were excluded from the database.

The present review aims to show the importance of each system, but to promote integrated systems or combined ones to find solutions that can lead to sustainable buildings. The only study found is the one of Pirouz et al. [23] that investigated the potential of combining fog harvesting systems with green walls while considering the water consumption of green walls in various climates and other associated factors. The researchers proposed a combined design based on their findings, see Figure 6.

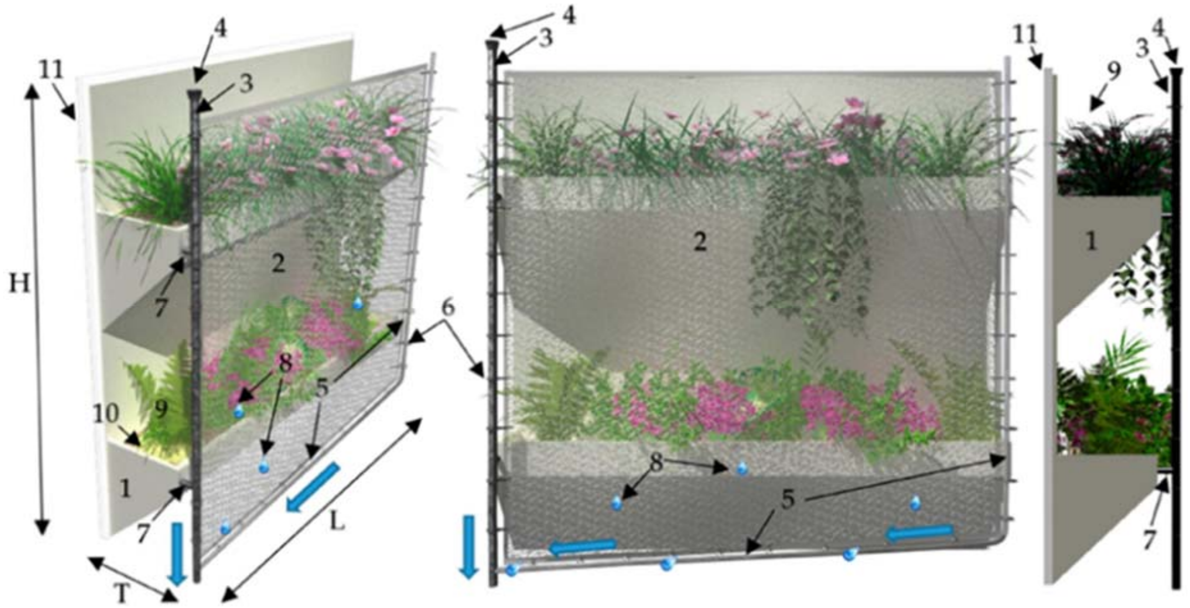

Figure 6. The innovative living wall platform incorporating a fog harvesting mesh is depicted as follows: 1—living wall platform, 2—fog harvesting mesh, 3—water collector pipe, 4—funnel connected to the collector pipe for water drop collection, 5—rod facilitating water drop conveyance to the collector pipe, 6—metal clamp securing the mesh to the pipe and rod, 7—support for affixing the mesh system to the green wall platform, 8—water droplets, 9—plants, 10—soil, 11—frame for securing the living wall to the building's wall, H—height of the platform, L—length of the platform, T—thickness of the platform. Source: [23].

However, in contrast to their approach, this review recommends creating a gap between the green and fog harvesting systems to allow for proper airflow and water droplet collection. On the other hand, the researchers agree with the statement provided by Pirouz et al. [23] as it points out the lack of studies investigating the use of fog harvesting systems to irrigate green walls, while studies on green walls and fog harvesting systems could be found separately.

6. Discussion and Conceptual Proposal

Direct and indirect greening systems present themselves as favorable environmental solutions, exhibiting commendable air quality and manageable maintenance requirements. It is important to note that living wall systems offer a broader spectrum of species and structures, facilitating the ease of application in certain situations, notwithstanding the associated economic and environmental burdens. Depending on the building's location, purpose, and the selected plant species, the green-and-blue system should be concurrently designed. However, the development of a supporting structure for the fog harvesting system, as a second layer of the façade, would provide shading, therefore increasing the possibility of applying species that grow better in shade, such as some kind of climbing plants.

In order to incorporate fog harvesting systems into urban environments and building designs, the device's structure must be carefully developed. This entails analyzing project requirements and determining design criteria. While fog water alone may not be sufficient to meet the water needs of an entire building, it can alleviate the burden on traditional freshwater resources, which are often overexploited.

Fog harvesting projects are usually developed with the primary focus of aiding agricultural endeavours in rural areas [73]. Nonetheless, it is imperative to explore and advance the potential of fog collectors to provide additional water resources for industrial and residential use. The construction industry, while being notably impactful on the environment, is experiencing a gradual rise in both water consumption and carbon dioxide emissions. These factors contribute to elevated air temperatures. Given that we will not be self-sufficient in fossil fuels before 2050, the revaluation of natural systems becomes crucial to address the current challenge that threatens the entire planet [79]. One of the fundamental aspects to achieve sustainable construction is archived working in synergy with nature and imitating it. Buildings must become resilient to the changing scenario in which they are located, due to climate change, adapting to climatic and physical conditions through the rationalization of the use of resources and energy. Therefore, the European Commission has delineated specific guidelines aimed at attaining the Near-Zero-Energy Buildings (NZEB) target by the year 2020 [80]. Moreover, in 2022, the United Nations also updated the 17 sustainable development goals (SDGs). Some of these can be achieved by applying a new sustainable enclosure on buildings. This review demonstrates that it could be helpful for researchers and urban planners to develop combined systems (blue and green), to encourage healthy and sustainable cities (SDGs 11), reduce the impact of climate change (SDGs 13), and be more responsible in energy consumption (SDGs 12).

Several of these objectives can be accomplished through the implementation of an innovative sustainable building envelope. The suggested experimental envelope incorporates a double façade, wherein the primary layer serves as the primary closure of the building, and the outer layer comprises the smart mesh. This versatile textile façade operates as a passive and 'Km 0' system, as it does not necessitate energy for water collection or distribution and is situated in close proximity to the users, deviating from conventional water distribution systems [81]. Given that the outer layer is composed of a mesh, it has the potential to offer shading, thereby reducing the demand for the cooling system during the summer, which otherwise entails substantial energy consumption and associated emissions [82].

In the event of integrating vegetation into the envelope, the façade has the potential to contribute to air purification. This is facilitated by both the filtering capacity of the mesh and the air-purifying properties inherent in the plants. It is crucial to emphasize that the presence of fog is not consistent throughout the entire year, contingent upon the characteristics of the location. The conceptual apparatus is designed with a focus on Mediterranean climatic conditions, where water collection is predominant during winter nights and early mornings, and shading is primarily essential in the context of summer days. Furthermore, each component of the envelope is better suited for specific functionalities, see Figure 7.

The size and placement of storage for collected water must be strategically planned, contingent upon the quantity and intended usage. Storage locations may include the basement or rooftop. In cases where the collected water serves solely for irrigation, like gardening, an autonomous system can be implemented. A notable application of this concept is demonstrated by the proposed model, which is adaptable and customizable for any fog oasis, aligning with external conditions and fulfilling the specific needs of users. The design methodology of this sustainable façade is intricately linked to the stipulated requirements of the fog collector and building envelopes. As such, it should incorporate modules that can be oriented to capture fog in the wind direction and to provide shading by aligning with the sun's trajectory, see Figure 8.

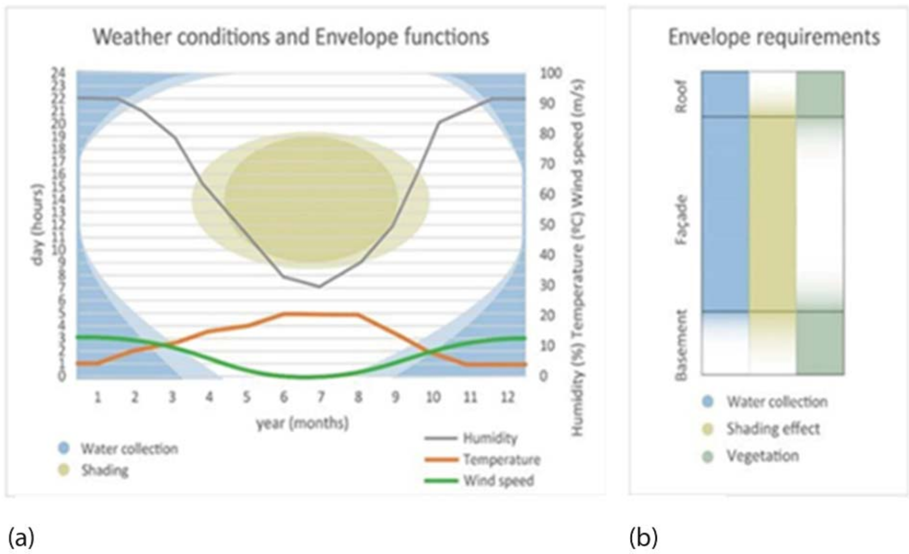

Figure 7. (**a**) Meteorological conditions and envelope functions—the correlation between meteorological conditions and the corresponding envelope functions throughout the day in a standard year. (**b**) Envelope criteria—water collection, shading, and vegetation are strategically positioned on distinct sections of the envelope, not only to enhance user comfort but also considering functional aspects. Source: graphic by the author: M.G. Di Bitonto.

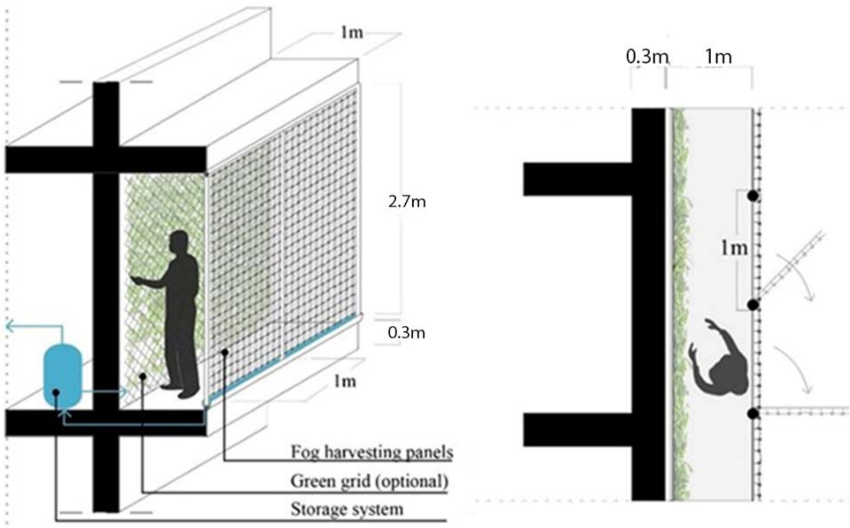

Figure 8. Facade concept—illustration of fog harvesting project advancements in the construction industry. Source: graphic by the authors: L. Hadba and M. G. Di Bitonto.

In an urban context characterized by lower wind speeds, the proposed facade configuration incorporates fewer fog-collecting modules. As a result, maintenance for the suggested facade primarily involves gutter cleaning, and the longevity of the fog collector is contingent upon the selected mesh's lifespan. Considering the introduction of this innovative application, the potential of a fog harvesting facade should be systematically explored through test campaigns, both in the field within a fog oasis and in controlled laboratory conditions. These tests aim to comprehend the mesh's behavior when exposed to varying wind velocities and facade dimensions. The development of such a facade necessitates a parametric design to accommodate all relevant variables, aligning with the specific characteristics of the location, building, and water collection objectives. In the context of maintenance, Holmes, Rivera, and Jara [75] highlight that the vulnerability of large fog collectors (LFC) lies in the mesh. This vulnerability often results in breakage due to high wind velocities, typically exceeding 17 m/s. Hence, employing a smaller mesh size can mitigate the risk of damage.

7. Conclusions

In light of the existing challenges related to the mismanagement of traditional resources and the outlined sustainability objectives across various sectors, including construction, the introduction of an innovative architectural solution holds significant potential for improving building performance. The proposed smart green textile facade has the capability to render the building envelope water self-sufficient, thereby reducing the ecological footprint and energy demand. Thus, even if fog harvesting is considered to be a new technology that may encounter hurdles like cost, awareness, and technical challenges, its application for irrigating green facades could be intriguing. This utilization may position fog harvesting as a potential complementary system, supporting existing structures like green walls.

The potential of implementing fog harvesting on building facades represents a novel and unexplored application area. It warrants thorough investigation through experimental campaigns conducted both in the field within fog oases and in laboratory settings. These campaigns aim to comprehend the fabric's behavior when positioned in front of a solid surface, considering variable wind speeds and facade dimensions. The development of such a facade necessitates a parametric design approach to model it comprehensively, accounting for all pertinent variables. This includes reflecting the specific characteristics of the location, the building, and the intended water usage.

The design process is contingent on numerous factors, encompassing local climatic conditions, the characteristics of the building to which it can be affixed, and the specific water demand and usage requirements. To facilitate the design development, parametric tools, along with an experimental campaign, are essential. It is worth noting that the effectiveness of fog collection has been verified in diverse global regions. Nonetheless, the novel solution necessitates validation and fine-tuning to meet specific requirements and demands.

As was presented, the collection of mist water combined with the development of vegetation is an innovative solution that has the possibility to achieve some of the sustainability goals in built-up areas, not only in rural but also in urban areas. The fog collector device must be studied and designed to adapt to the established function in relation to the type of green wall. Futhermore, the study underscores the necessity of a multi-disciplinary approach, merging architectural design, environmental science, and urban planning. Collaboration across these fields is vital for crafting effective and sustainable solutions.

In conclusion, using green systems on the facade of a building plays an important role visually but also offers substantial benefits such as mitigation of air pollution, improvement of thermal comfort, reduction in noise pollution, and promotion of overall well-being, and combined with a new technique to collect water, it could aid the implementation of green walls in areas with a good amount of fog episodes but are in need of running water for domestic and other purposes.

Thus, a resolute call to action directed towards urban development stakeholders is necessary, including architects, planners, policymakers, and communities. Emphasizing the potential presented by the integration of sustainable systems for a resilient future, this appeal highlights the adaptability of the project. Its flexibility can be tailored to diverse settings by adjusting material choices, mesh configurations, and plant selections, catering to varying urban fabrics, climates, and layouts.

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