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Review

Health and Well-Being Benefits of Outdoor and Indoor Vertical Greening Systems: A Review

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Abstract: Green spaces have become the most threatened by urban growth, and the decline in these areas is a main cause of environmental and social problems with implications for human health and well-being. Vertical greenery systems have been proposed as a solution to restore the connection between the city and nature, particularly in compact and dense cities, where horizontal space is limited. This paper provides a literature review to examine the influence of outdoor and indoor vertical greenery systems on human health and well-being. The Web of Science and Scopus databases were chosen to survey peer-reviewed documents published until October 2022. A total of 73 documents were selected by the search. Over 71% of the documents were published over the last four years, and most of them focused on the environmental and thermal benefits of vertical greenery systems. Although these benefits could bring health and well-being outcomes, they were not objectively measured and quantified. Other additional gaps and guidelines for future research were also identified and discussed. This review could be helpful for researchers and urban planners in developing vertical greenery to create healthy and more sustainable cities.

Keywords: vertical greenery systems; green wall; green façade; living wall; urban greenery; health; well-being; sustainability

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1. Introduction

According to the World Health Organization, health is a state of complete physical, mental, and social well-being, and not merely the absence of disease or infirmity [1]. Studies have demonstrated that urban green spaces and other nature-based solutions have a positive impact on various dimensions of human health and well-being. First, these spaces mitigate the effects of various forms of pollution. Urban vegetation has an important role in cleaning the air from pollutants by filtering and absorbing some gases and retaining particles that can be harmful to humans [2–4]. Urban vegetation has also been reported for its noise barrier effect, namely from traffic, which is the main source of noise in urban spaces [5,6]. Due to shade and evapotranspiration, green spaces help to regulate the urban thermal balance, attenuating the urban heat island effect and controlling the buildings' thermal balance, which results in important energy savings and increased indoor comfort [7]. Second, urban green spaces foster social interactions and provide recreational opportunities, which help in improving well-being [8,9]. Additionally, third, urban green spaces have been reported to reduce stress, anxiety, depression, and other mental and physiological diseases [9–11]. For example, recent studies carried out during the COVID-19 pandemic indicated a positive association between urban parks and human health [1]. A study carried out by Falco et al. [12] also suggested that more public green areas were associated with less severe COVID-19 clinical outcomes in terms of contagion, hospitalizations, and especially deaths. Other studies showed that the public importance given to green spaces increased substantially during the pandemic [13,14].

Urban green spaces can be understood as the sum of all green areas, which includes parks, gardens, recreational areas, open spaces, residential gardens, tree-lined streets, green roofs, and vertical greenery systems, among other forms [13,15]. Vertical greenery systems (VGSs) refer to plants grown on a vertical profile through structures and modular systems. VGSs usually include a multitude of forms and concepts, such as vertical gardens, green walls, green façades, vertical greens, vertical landscaping, living walls, and bio-shaders [16]. In practical terms, these various concepts can be categorized as green façades and living walls [16]. A green façade generally refers to climbing or cascading plants grown on or adjoining a building surface rooted at the bottom of the building, while a living wall refers to plants grown in planter boxes which can be developed into modular systems attached to walls [16]. As adopted in previous works, this paper uses the concept of VGS to describe all forms of plants that are grown vertically on buildings [16,17].

In the urban context, the growing interest in VGS is mainly explained by two main factors: (i) the lack of available horizontal space to create conventional green spaces and (ii) the high market price of the available space, which also restricts the creation of horizontal green spaces [18]. VGSs can increase vegetation cover in built-up areas without consuming space, and they can be applied to the enormous available wall area in cities. In turn, indoor VGSs use less space than other interior plants, such as potted plants. Thus, VGSs have been developed as a sustainable building solution to increase vegetation cover in built-up areas [2].

The literature on urban greening has substantially increased over the last two decades, but as emphasized by Rowe et al. [19], most of these studies only consider parks/public gardens and trees. This shows the need for future studies to assess whether VGSs have the same beneficial effects as other urban green spaces. Although the research on VGSs has gained importance in recent years [20], previous evidence on the associations between VGS and human health and well-being is considered an under-researched topic [19,21,22]. In addition, the literature on VGS has mostly explored the impact of outdoor vertical greenery and how it affects the physical environment, while the benefits of indoor vertical greenery have not been fully analyzed [23]. To fill these gaps, this paper reviews the literature relating VGSs to health and well-being and presents their findings systematically. The main purpose of this review is to examine the health and well-being benefits of outdoor and indoor VGS, show research trends, identify knowledge gaps, and make research recommendations for future work to promote VGS as a design solution with the potential to create healthy and sustainable cities.

The remaining sections of this paper are organized as follows. Section 2 describes the methodology adopted for data extraction. Section 3 presents the results and main findings of the conducted review. Section 4 discusses the results, while Section 5 concludes the work by identifying literature gaps and providing recommendations for future research.

2. Materials and Methods

The literature review was conducted according to the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) guidelines. As shown in Figure 1, the four main steps of this review were (i) the identification of relevant articles; (ii) screening according to established criteria; (iii) the extraction of the selected articles; and (iv) classification according to topics and their methods.

For the first step, a search was made in the literature using the Scopus and Web of Science databases, which have been widely used for performing reviews and are considered consistent repositories to search for scientific publications [24]. The search was conducted by using the following terms in the title, abstract, and keywords of publications: [green façade; living wall; vertical garden; green wall; vertical greening system] AND [health; well-being]. The search was restricted to peer-reviewed documents written in English and published as journal articles from the inception of the electronic bibliographic databases to 31 October 2022.

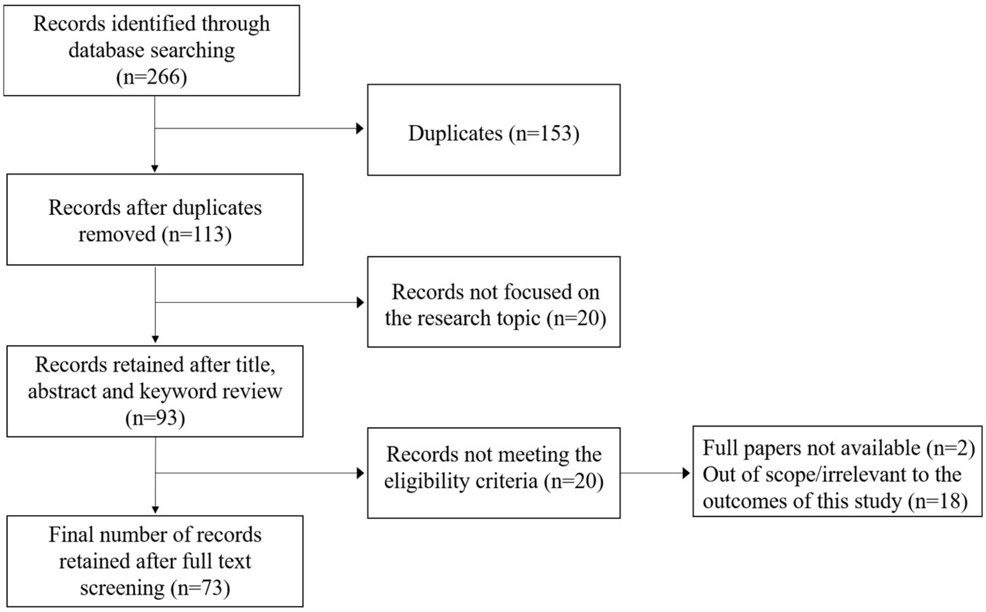

Figure 1. Flow diagram of literature review.

In the second step, the articles' reference lists were reviewed to detect any studies that may have been missed. The screening process consisted of evaluating the eligibility of the returned articles. Titles, abstracts, keywords, and, whenever necessary, full texts were manually checked to determine which of these publications predominantly deal with the influence of the searched terms on health and well-being. Duplicated publications on the two databases and documents without full texts were excluded. Studies were independently double-screened by two members, and differences were resolved through discussion and consensus.

After the articles were selected, the respective data were extracted. This included article title, authors, keywords, year of publication, publication title, and full texts, among others. The retrieved information was then used to conduct a brief bibliometric analysis to ascertain research growth on this topic, leading sources, authors, and respective research centers.

Finally, the extracted articles were classified according to their topics and methods. As suggested by Shao et al. [23], the literature on VGS was firstly divided into outdoor and indoor green wall systems, and then each theme was subdivided into the following seven topics: air pollution/air quality, thermal comfort/energy efficiency, noise reduction, social perceptions, health/well-being, design solutions, literature review, and other issues. The articles were also organized according to their research methods by considering the following categories adapted from Wimalasooriya et al. [25]: experimental, observational, simulation, questionnaire, review, descriptive, and mixed.

According to the described steps, a total of 266 references were identified from Scopus and Web of Science. After 153 duplicates were removed, 113 records were screened based on the title, abstract, and keywords. From these, 20 records were excluded as they were not related to the research topic. This included some studies where the term "green wall" was not related to VGS but to the Great Green Wall tree-planting initiative in the Sahel region, as well as studies focused on the water needs of plants, greywater treatment to irrigate plants, fungal and bacterial dynamics in green walls, and lifecycle assessment of plants, among other topics. Thus, 93 records were assessed for eligibility by full-text screening. The full-text screening excluded two records that we were unable to be retrieved due to a lack of full access to the paper, while a total of 17 records were excluded because they were out of scope or irrelevant for the goals of this review. This mainly includes records in which the searched terms used in the title, abstract, or keywords were not explored in depth in the papers. Therefore, 73 records were eligible for review.

3. Results

3.1. Overview of the Included Studies

The 73 eligible records were published between 2008 and 2022, but the searched topic has gained increasing attention over the last four years, which was when 71% of the documents were published (Figure 2). All the retrieved documents were published as articles in a total of 45 journals. Research into VGS has been published in various subject areas, including environmental sciences, engineering, planning, material sciences, and social sciences. The journals with the most publications are Building and Environment (10 publications), Urban Forestry & Urban Greening (7), Journal of Cleaner Production (4), and Sustainability (4).

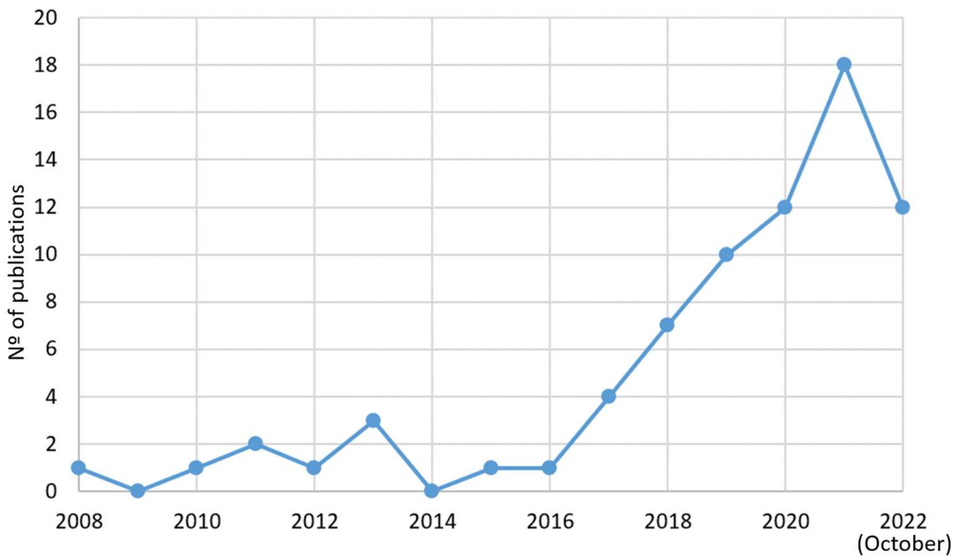

Figure 2. Number of papers published by year.

The 73 documents contain about 400 keywords. From these, the keywords with more than 10 occurrences are: "green wall" (this appears in 31 documents), "living wall" (17), "Green infrastructure" (15), "air quality" (13), and "green roof" (12). The remaining keywords with more than four occurrences are shown in Figure 3.

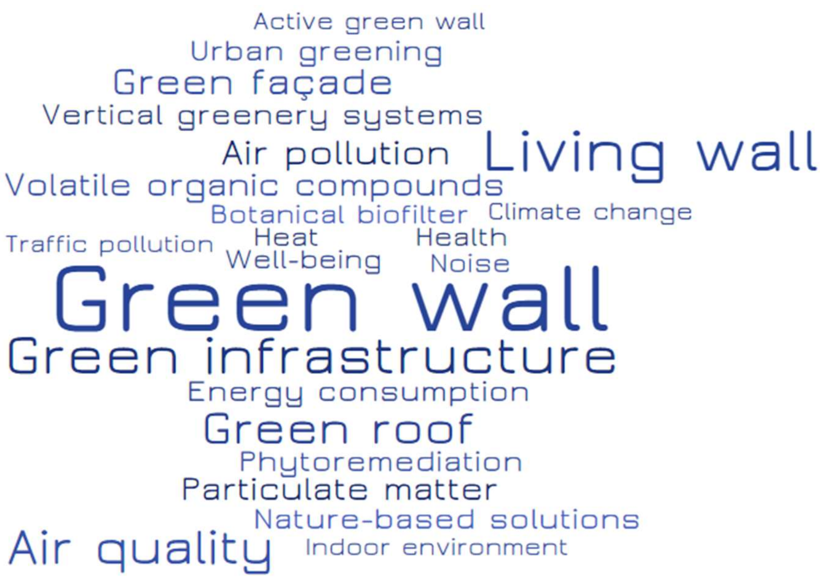

Figure 3. Authors' keyword density diagram.

The University of Technology Sydney is the institution with the most publications on the searched topic, due to the research performed by Peter Irga, Thomas Pettit, Naomi Paull, Fraser Torpy, and Robert Irga. The Delft University of Technology and the University of Seville should also be emphasized, owing to the works of Marc Ottelé, Alex Fraaij, and Luis Urrestarazu and their teams.

According to Scopus, the five most cited studies within this field until October 2022 were the article by Norton et al. [26], with 533 citations, followed by the studies carried out by Currie et al. [27], with 220 citations; Ottelé et al. [28], with 218; Ottelé et al. [29], with 202; and Zhao et al. [30] with 127 citations.

Of the 73 articles, 27 (37%) were related to air pollution/air quality, which was the most studied topic. The following most researched topics were thermal comfort/energy efficiency (19%), health and well-being (14%), design solutions (8%), noise reduction (6%), and social perceptions (6%). In addition, 9% were review studies, while around 1% correspond to other issues.

The countries with two or more case studies are shown in Figure 4. Research into the searched terms has been most popular in Australia, Southern Europe countries (Spain, Italy, and Portugal), China, and Middle Eastern countries, indicating that these studies have been mostly conducted in areas with hot, subtropical, and Mediterranean climates. As shown in Figure 4, thermal comfort/energy efficiency, air pollution/air quality, and health/well-being have been the most studied topics in these countries.

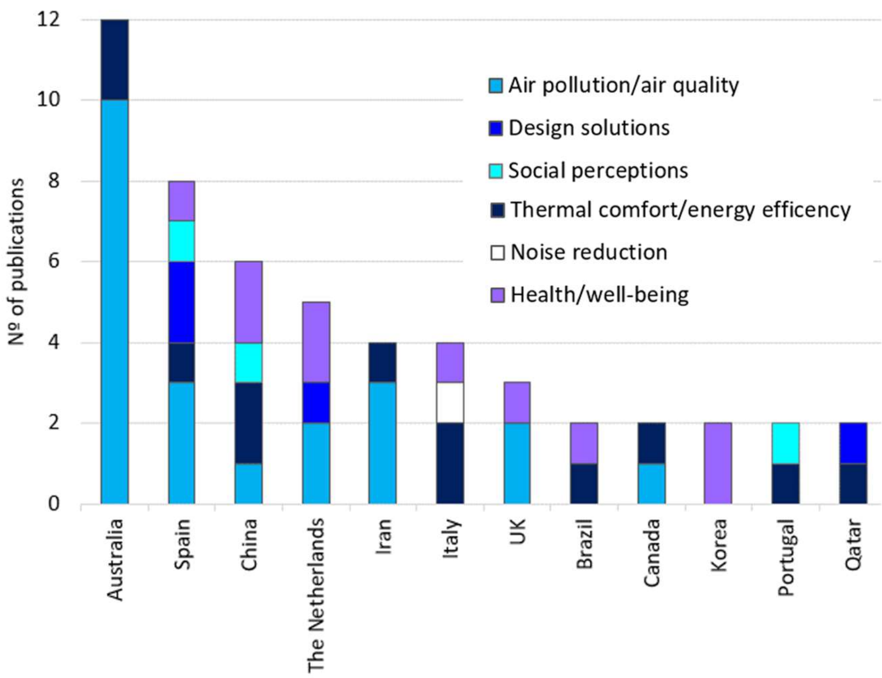

Figure 4. Case studies by country and respective topics.

Finally, in terms of scope, 53% of the records have an outdoor scope, 37% have an indoor scope, and 10% are not within this classification. As shown in Table 1, most of the outdoor and indoor studies were conducted within the air pollution/air quality topic (39% and 44%, respectively). In the outdoor scope, the following most representative topics were thermal comfort/energy efficiency (28%) and design solutions (13%). In the case of indoor VGS, health/well-being was the second most representative topic (30%), followed by thermal comfort/energy efficiency (11%). A detailed overview of the studies in this review by the main scope, respective topics, and methods is shown in Table 1. The main findings are described in the next subsections.

Table 1. Scope, topics and methods on the searched documents.

	Topics								
	AP/AQ	**TC/EE**	**NR**	**SP**	**H/WB**	**DS**	**LR**	**OI**	**Method**
Abedi et al. [31]	•								E
Anderson et al. [32]		○							D
Andric et al. [33]		○							S
Caron et al. [34]	•								E
Chàfer et al. [21]							X		R
Chang et al. [35]			○						E
Convertino et al. [36]		○							O
Currie et al. [27]	○								O
Davis et al. [37]			•						E
De Lucia et al. [38]		•							E
Elsadek et al. [22]					○				O
Feitosa et al. [39]		○							O
Fensterseifer et al. [40]		○							O
Flores et al. [41]		•							O
Ghazalli et al. 2018 [42]	•								O
Ghazalli et al. [17]							X		R
Gunn et al. [43]					•				Q
Han et al. [44]		○							M
He et al. [45]	○								O
Hop et al. [46]							X		R
Hozhabralsadat et al. [47]	○								O
Irga et al. [48]	•								E
Kazemi et al. [49]	•								E
Kyrkou et al. [50]					•				D
Li et al. [51]					•				M
Liberalesso et al. [52]				○					Q
Mannan & Al-Ghamdi [53]						•			O
McCullough et al. [54]								X	D
Moghaddam et al. [55]						○			S
Morgan et al. [56]	•								E
Norton et al. [26]		○							D
Ottelé et al. [28]	○								E
Ottelé et al. [57]	○								E
Ottelé et al. [29]						○			O
Parhizkar et al. [58]		•							E
Paull et al. [59]	○								E
Paull et al. [60]	○								E
Pettit et al. [61]	•								E
Pettit et al. [62]	•								E
Pettit et al. [63]	•								E
Pettit et al. [64]	○								E
Pettit et al. [65]	○								E
Pichlhöfer et al. [66]	•								O
Rowe et al. [19]							X		R
Santiago et al. [67]	○								S
Scamoni et al. [68]			•						E
Senosiain et al. [69]		○							D
Silva et al. [70]						○			O
Srbinovska et al. [71]	○								O
Suárez-Cáceres et al. [72]	•								E
Suárez-Cáceres et al. [73]	•								E
Talhouk et al. [74]					○				Q
Tarboush et al. [75]				○					Q
Thorpert et al. [76]						○			O
Tomson et al. [77]	○								O
Urbano-López [78]							X		R

Table 1. *Cont.*

	Topics								
	AP/AQ	**TC/EE**	**NR**	**SP**	**H/WB**	**DS**	**LR**	**OI**	**Method**
Urrestarazu & Burés [79]						○			D
Urrestarazu et al. [80]				○					Q
Urrestarazu et al. [81]					•				Q
Van den Berg et al. [82]					•				M
Van den Bogerd et al. [83]					•				M
Van Renterghem et al. [84]			○						O
Vera et al. [85]	○								E
Yeom et al. [86]					•				M
Yeom et al. [87]					•				M
Wahba et al. [88]		○							S
Weerakkody et al. [89]	○								E
Weerakkody et al. [90]	○								E
Zhang et al. [91]				○					Q
Zhao et al. [30]							X		R
Zhu et al. [92]		○							S
Zinia et al. [93]		○							Q
Zivkovic et al. [94]							X		R

Scope: ○ Outdoor; • Indoor; X Not applicable. Topic abbreviations: AP/AQ: air pollution/air quality; TC/EE: thermal comfort/energy efficiency; NR: noise reduction; SP: social perceptions; H/WB: health/well-being; DS: design solutions; LR: literature review; OI: other issues. Method abbreviations: E: Experimental; O: Observational; S: Simulation; Q: Questionnaire; R: Review; D: Descriptive; M: Mixed.

3.2. Findings

3.2.1. Air Pollution/Air Quality

According to the World Health Organization (WHO), air pollution is considered the most hazardous type of pollution in urban spaces. Various studies found within this review show that outdoor VGS can improve air quality and reduce air pollution, namely particulate matter (PM), a main air contaminant that causes serious health threats [57]. For example, Srbinovska et al. [71] found that green infrastructure, including green walls, reduces PM2.5 on average by 25% and PM10 on average by 37% when compared to non-green areas. Studies carried out by Ottelé et al. [28,57] showed that leaves perform a sink function for significant quantities of health-damaging fine and ultra-particles (<10 μm diameter). Various studies were conducted to understand the ability of different plant species to reduce PMs [47,77,85,89]. Although different species captured different quantities of PMs, the use of VGS with smaller-leaved species and leaf needles can potentially be more efficient in removing PMs [45,47,89]. Other variables, such as traffic volume and the place/design of the walls, also influence the plant's performance in removing PMs. In this context, He et al. [45] concluded that the amount of accumulated PMs by roadside plants increases with traffic volume. A study by Vera et al. [85] indicated that the greater the biodiversity of plants, the higher the PM2.5 captured. Similarly, plants installed in green walls with heterogeneous topography result in a significantly higher capture of PMs [90]. Other studies also demonstrated that some plant species are able to withstand continual ambient pollutant exposure with minimal damage [59,60]. Green infrastructure is also efficient in taking up other air pollutants. For instance, Pettit et al. [64] found that a green wall was able to filter O_3, PM2.5, and particularly NO_2 from wildfire emissions, while in a more recent study, Pettit et al. [65] reported that three botanical biofilters installed in walls reduced the concentrations of NO_2, O_3, and PM2.5 from road traffic. Currie et al. [27] showed that green roofs and green walls can complement, and almost equal, the capacity of existing trees in removing air contaminants such as NO_2, SO_2, CO, and PM10. Inversely, Santiago et al. [67] found that trees and hedgerows were more effective in reducing traffic pollutants than green walls and green roofs, which have a more restricted effect on the building surface areas.

Indoor air quality has been receiving increased attention because, on average, people spend 80% of their time in confined environments [34,49]. For this reason, the health risks of indoor air pollution can be greater than those of outdoor air pollution [49]. Outdoor VGS and overall urban green infrastructure may help to improve indoor air quality. However, indoor VGS can reinforce and complement the role of outdoor vegetation. Indoor VGS are considered a viable phytoremediation solution to remove air pollutants such as volatile organic compounds (VOCs) and PMs without consuming much space [72]. For example, Abedi et al. [31] found that plants have a single-pass removal efficiency of 13.5–28.1% of formaldehyde (a frequent indoor VOC) and a clean-air delivery rate of 0.39–5.46 m^3/h. In another study, a green wall helped to reduce the total injected oxygenated VOC concentration by 27 ppb (parts per billion) when compared with a room without a green wall [34]. Morgan et al. [56] showed that a green wall module removed 43% of cigarette-associated VOCs and 34% of total suspended particles from the air. In a study by Pettit et al. [62] conducted in a residential room and in a classroom, the installation of a green wall reduced the concentrations of VOCs and PMs by 72.5% in the room and by 28% and 43%, respectively, in the classroom. Ghazalli et al. [42] also found that introducing vertical greenery in a corridor contributed to decreasing PM 2.5 by 49% and PM10 by 87% over the duration of the study. In another experiment, Pettit et al. [63] revealed that two common indoor plant species helped to reduce ambient NO2. Long-term exposure also tends to increase the total VOCs removed by vegetation. An experiment performed by Suárez et al. [72] showed a substantial reduction in total VOCs, ranging from 13% for short periods up to 77–93% for longer periods (after 70 h). As confirmed in various studies [48,49,61,66,73], the efficiency for removing different types of VOCs and other indoor pollutants also depends on the plant species selected for living walls.

3.2.2. Thermal Comfort/Energy Efficiency

High outdoor temperatures result in high indoor temperatures, which is a main determinant of human comfort, health, and well-being. For example, a study by Flores et al. [41] shows that the number of medical consultations increased by 15% when indoor air temperatures reached 33 °C or more during hot periods. VGS can improve the thermal balance and comfort of buildings, reducing the energy and the costs associated with cooling. There is considerable evidence that air temperatures are often higher in bare walls than in green walls [36]. For example, in Brazil, Fensterseifer et al. [40] found that a green wall reduced the thermal amplitude and the variability of the wall temperatures especially during the summer by up to 9 °C, while in Sydney, Feitosa et al. [39] noted that adding green roofs and green walls to buildings would decrease indoor temperatures up to 8.3 °C in the summer. In Spain, Senosiain et al. [69] showed that greening part of buildings within urban regeneration projects would decrease the cooling energy demand by 10–15%. In Cairo, Wahba et al. [88] estimated that green building envelopes may decrease indoor temperature by 5 °C and save energy with cooling from 17% up to 25%.

Installing indoor VGS may also reinforce and complement the cooling effect of outdoor VGS. The temperature around the plants decreases through evapotranspiration, and this process helps to cool the air [49]. A study carried out by Parhizkar et al. [58] showed that 5 square meter (m^2) of Azolla (a plant) per person would reduce fresh air ventilation demand by almost 30%. After installing an indoor green module, De Lucia et al. [38] found a reduction in the heat flow per unit of time and surface ranging from between 42–62% (perimeter wall) to between 83–92% (internal partition). Inversely, Ghazalli et al. [42] concluded that introducing vertical greenery in a corridor does not have a relevant impact on reducing indoor air temperature. As in the case of outdoor VGS, it was found that some indoor plant species (and growing media) have more cooling potential than others [38,49].

Other authors have proposed integrated planning frameworks [26,32] and retrofit design solutions [33,44,92] to improve the thermal comfort/energy efficiency of VGS. According to the planning framework of Norton et al. [26], green walls should be prioritized for dark-colored walls with high solar exposure, narrow streets, and streets with aerial obstructions where trees are unviable. In terms of integrated design solutions, VGS have been proposed in combination with other thermal insulation measures, although their cooling performance could be lower, particularly in hot climates. For example, in Qatar, Andric et al. [33] found that the addition of 5 cm expanded polystyrene and the installation of energy-efficient windows was more efficient in reducing energy with cooling than the addition of green walls and roofs. Similarly, Han et al. [44] also showed that the combination of green walls with other sunshades and water surfaces will produce better thermal comfort in a sunken courtyard than just using a green wall. Zhu et al. [92] highlighted that although green walls had positive effects on cooling façades, the use of cool pavement has more potential to decrease the canopy air temperature.

3.2.3. Noise Reduction

According to the WHO, noise is the second most important cause of health problems, especially from disturbing people's rest. Studies have shown that VGS can reduce indoor noise. For example, in a study developed by Van Renterghem et al. [84], green walls in inner-city buildings attenuated traffic noise from 2.6 to 5.1 dBA. Through laboratory and in situ evaluations, Scamoni et al. [68] also found that a living wall promoted the acoustic insulation of the base wall by 6 dB. They also noted that large-leaved plants had a higher absorption at medium-high frequencies, while small-leaved plants performed better at high frequencies. In another study conducted to evaluate the sound absorption of a living wall, Chang et al. [35] concluded that the module increased the sound absorption at all octave bands, and the highest effectiveness was in the mid-high frequencies. The noise absorption in a green wall also comes from the substrate, particularly in modular walls. This conclusion can be found in a study by Davis et al. [37], who developed and tested a vertical garden design for interior acoustic design.

3.2.4. Social Perceptions

Citizens generally have positive attitudes towards green infrastructure elements [80]. This is also true for small green infrastructures such as VGS. For example, the installation of a green wall in a hospital in Seville (Spain) induced positive reactions and improved the psychological well-being of 82% of the participants in the study by Urrestarazu et al. [80]. In Cyprus, 84% of the participants in the study by Tarboush et al. [75] regarded green walls as an important solution to reduce air temperature, while 83% supported the application of green walls in Nicosia. In Guangzhou (China), Zhang et al. [91] showed that small urban green infrastructures (which include green walls) are widely welcomed and regarded as essential elements in daily lives, namely by younger groups, who are more likely to recognize their benefits.

On a different note, some studies have indicated that VGS could have less social acceptance. This was found in Dhaka (Bangladesh), where most of the participants in the study by Zinia et al. [93] preferred rooftop garden/agriculture as the most implementable adaptation strategy. They found that green walls were not culturally appreciated in the city. Similarly, a study carried out in Lisbon by Liberalesso et al. [52] revealed that although the installation of green roofs and walls in hostels is supported by the public, having a green envelope was not a relevant reason for selecting a hostel, and some groups (such as males) were not willing to pay higher rates to stay in these hostels.

3.2.5. Health/Well-Being

In general, the literature provides evidence that green spaces are associated with physiological and psychological health and well-being benefits [15]. Although not entirely consensual, particularly in the case of indoor living walls, VGSs make people feel better, reduce stress [17], and increase the task load [87]. Evidence for this can be found in a study carried out by Elsadek et al. [22], who analyzed the relaxation effects of visualizing two urban environments (a building wall and a green façade). The brain activity, heart rate variability, and skin conductance tests indicated that seeing the green façade evokes a sense of relaxation and reduces stress. During the COVID-19 lockdowns, Urrestarazu et al. [81] studied the impact of having plants at home on people's emotional welfare. For 74% of the participants in this study, indoor vegetation had psychological well-being benefits, for example, by taking care of plants. Similarly, Talhouk et al. [74] revealed that vertical gardening helped to decrease depression and stress, helped with socialization, and promoted well-being among women refugees in Lebanon. However, some studies on the effect of indoor VGS on health/well-being are more inconclusive. For example, Li et al. [51] reported that negative emotions tended to decrease as the number of green walls increased, but when the greenery dose was too high, the physiological relaxation decreased. They recommended a biophilic environment with three green walls for effective psychological regulation. Similarly, Yeom et al. [86] found that installing a small indoor green wall could have a more relaxing effect than a large green wall.

Various studies have also examined the potential benefits of implementing indoor green walls in schools and health facilities. In schools, there is evidence that indoor vegetation reduces the levels of stress and anxiety and increases well-being and the mood of children [43]. In addition, it was found that children in classrooms with indoor VGSs scored better in selective attention tests, assigned more positive evaluations to their classrooms, and obtained higher lecture evaluations than children in classrooms without green walls [82,83]. However, these two studies did not report measurable effects of VGS on children's self-reported well-being, which could be explained by their short exposure [83]. In health facilities, vegetation and VGS help in eliminating negative feelings and promote healing. According to Kyrkou et al. [50], vegetation may speed patients' recovery processes and lead to a less traumatic overall experience during hospitalization. This was also confirmed by Urrestarazu et al. [80] in a study conducted in a hospital in Seville: 82% of the participants associated a green wall with improved well-being.

3.2.6. Design Solutions

Different greening systems may have different environmental performances, as well as different costs in terms of materials, maintenance over time, plant density, nutrients, and water, among others. Within this topic, a study by Ottelé et al. [29] showed that indirect greening and living wall systems have a major environmental burden due to using more materials (planter boxes and felt layers) and their short life span compared to direct greening systems. Moghaddam et al. [55] showed that the density of plants and the size of cavity depth (the space between the wall and the structure) have a direct impact on the performance of a green wall: a façade 100% covered by plants will increase heat attenuation, while a façade 50% covered by plants will increase ventilation effects. To reduce the environmental burden of these structures, some authors developed modular green wall prototypes made of recycled and recyclable materials [53,79]. In a different field, research conducted by Thorpert et al. [76] revealed that it is possible to design a living wall based on color principles to deliver greater aesthetic appreciation and enjoyment from plants.

In turn, cost quantification of VGS is apparently an under-explored issue in the literature. The only study found in this field [70] describes a life cycle cost–benefit analysis for greening a railway station in Lisbon. For a 50-year life cycle, the cost–benefit analysis showed that the five greening alternatives studied were economically feasible. The estimation indicated that the green façade alternative could lead to gains 50 times higher than the associated costs, while the alternative living wall could bring gains 10 times higher than its costs. In another study, the green wall installed in a hospital in Seville gave significant media visibility to the hospital, which was estimated at EUR 200,000 [80].

3.2.7. Literature Review and Other Issues

A total of seven review papers were identified. Some authors conducted bibliometric reviews, e.g., a statistical and scientometric analysis, to map the scientific knowledge area and identify research trends and gaps. For example, the reviews conducted by

Chàfer et al. [21] and Zhao et al. [30] identified some common gaps, namely the lack of studies on the benefits of green façades and green walls, particularly on health.

Some authors reviewed urban planning practices to implement these greening solutions [78,94], while others focused on specific functions associated with urban greenery. For example, Hop et al. [46] reviewed the large-scale ecosystem services provided by ground-level urban vegetation, green roofs, and green walls and concluded that the contribution of green walls could be underestimated due to the reduced number of publications found at that time. More recently, a review conducted by Rowe et al. [19] concluded that more evidence on the benefits of VGSs is needed, particularly in terms of noise reduction, psychological and health effects, and biodiversity. Finally, Ghazalli et al. [17] reviewed the potential physical and non-physical contributions of VGS. They found that the impact of outdoor VGS has been much more analyzed, while indoor VGS and nonphysical benefits, such as health and well-being, have received little attention.

From a different perspective, McCullough et al. [54] developed a model curriculum based on the Green Wall Maker Workshop, which includes the study of living walls, the development of planting plans, and the fabrication and maintenance of living walls. The authors argued that the students' initiation with these topics at the elementary school level could potentially lead to their involvement in more sophisticated applications of green technologies in subsequent education levels.

3.3. Methods Used

As shown in Table 1, experimental research was the most used method, with 24 (33%) papers reviewed adopting experimental research, followed by 17 papers (23%) using an observational research method. The other methods were less adopted and included papers supported by questionnaires (11%), review articles (10%), descriptive studies (8%), papers adopting a mixed approach usually combining quantitative and qualitative evaluations (8%), and research based on simulations or modeling (7%).

A detailed topic analysis shows that air pollution/quality, thermal comfort/energy efficiency, and noise-reduction studies were mostly based on experimental research, which include laboratory settings and environmental test chambers to validate or evaluate specific solutions and approaches. In turn, observational research, e.g., based on data collection and direct observations were applied to almost all topics, mostly focusing on design solutions, air pollution/air quality, and thermal comfort/energy efficiency. Social perception studies were exclusively supported in questionnaires conducted to collect attitudes and ideas from specific individuals. Questionnaires were also commonly used in health/well-being studies in combination with mixed methodologies. Finally, simulation methods, usually performed as computational simulations, were more represented among thermal comfort/energy efficiency studies.

4. Discussion

This review was conducted to provide additional evidence on the contributions of VGSs to human health and well-being. The 73 analyzed documents focus on very different research fields, including environmental sciences, urban planning, engineering, acoustics, design, materials, and social studies. In general, the revised literature clearly indicates that VGS could be successfully used to improve air quality, enhance urban and building thermal comfort, attenuate unwanted noise, and create aesthetic and pleasant environments, which may bring various health and well-being benefits. Unlike what was described by Chàfer et al. [21], most of the studies found within this review are related to the environmental impact of VGS. It was found that both outdoor and indoor VGSs are very efficient in cleaning the air from pollutants, particularly from fine particles and VOCs that cause serious health threats. Although the efficiency of these greening solutions could be more restricted to the building and adjacent street canyon areas [67], they can complement the role of the remaining urban green infrastructure in removing pollutants from the air. Another contribution is the role that VGSs have in promoting building thermal comfort, in attenuating urban heat, and in mitigating extreme heat events, which have been associated with increased morbidity and mortality, particularly in deprived neighborhoods [26,41]. Most of the searched documents focused on building thermal comfort, showing that, depending on the climatic and seasonal conditions, VGSs can promote a substantial cooling effect up to 8 to 9 °C [39,40]. Although VGSs may also help to attenuate the urban heat island effect and cool street canyons [26,39], these contributions were not analyzed or quantified in the searched documents. It also seems that outdoor VGSs are more efficient in reducing indoor air temperature than indoor VGSs [42]. The thermal insulation provided by VGSs during cold seasons is another issue that has been under-analyzed. Although some authors have argued that VGSs reduce heat loss from the indoors to the outdoors [36,40], some studies have also shown that the insulation effect of VGSs may increase the building heat demand during the winter [33,95]. Thus, the thermal benefits of VGSs during the winter are still unclear and should be further studied. Another important contribution with health and well-being implications is the noise attenuation achieved by VGSs. Two of the studies carried out in this field showed reductions from 5.1 dBA to 6 dbA [68,84].

The environmental benefits and respective health outcomes associated with VGS depend on a multitude of variables. Selecting the most suitable plant species is critical for maximizing the performance of VGS in terms of thermal comfort, noise attenuation, and removal of air pollutants. Aspects such as plant size, growth habits, leaf shape and texture, and deciduous or evergreen, among others, should be considered according to the desired effect and the local conditions (façade orientation, wall types, building height, and water needs, among others.). For example, some studies have shown that needle-leaved conifers generally accumulated more PMs than broad-leaved species [47,89]. Other local variables that influence the environmental performance of VGS include the density of plants, cavity depth and type of modules, substrates, and materials used, such as felt geotextiles or polymeric materials [37,55], which provide different thermal and noise-insulation effects. These approaches are valuable to understand and disseminate the use of VGS. Local climatic conditions are also critical. Most of the searched documents are from countries with Mediterranean, subtropical, and hot climates. While there is evidence that VGS can reduce indoor air temperatures and contribute to saving energy with cooling in these regions [39,40], in arid climates, the cooling effect could be less effective [33]. In these climates, the installation of VGS could be complemented by other thermal insulation measures, such as double-glazed windows. However, extreme climates pose other issues to VGS that should be considered in terms of water needs, maintenance over time, and survival and durability of the plants.

In terms of social perceptions and health/well-being, the review showed that in general, people have positive attitudes towards VGSs [75,80] and that VGSs make people feel better, reduce stress and anxiety, increase the task load, improve attention, and promote healing. However, other authors found no associations between VGSs and well-being [82,83], while others noted that the benefits of the nature element on mood and well-being tend to decrease over time [43]. With few exceptions [22], these evaluations have been mostly supported by self-reported questionnaires during short periods of exposure to greenery. Thus, the associations between VGS and health/well-being are not entirely clear and should be further examined in future studies, preferably through physiological and psychological measurements and by involving large groups of individuals to avoid biased results. In addition, public perceptions towards VGSs were only found in a restricted number of papers [52,75,80]. Understanding the perceptions and opinions of the public about VGS in buildings is crucial to support the adoption of efficient planning measures. Thus, it seems that this topic should also be further analyzed. While the few studies specifically conducted on this topic showed that the public recognized the benefits of VGSs, the range of benefits was not equally evaluated or understood. The potential barriers to installing this green infrastructure, such as installations and maintenance costs, skills needed to care for the plants, and problems with insect pests such as mosquitoes, are particularly few/not examined. As noted by Jim et al. [96], the public should be more proactively and effectively included in the design, installation, and maintenance of VGSs and other greening solutions. While many authors have researched various design solutions and proposed more durable and sustainable materials for VGSs [53,79], the quantification of the installation and maintenance costs was only made by two authors in the searched documents. Silva et al. [70] describes a financial and economic viability study of greening a building, while Srbinovska et al. [71] detailed the installation and maintenance costs of a system built by them (250 EUR/m^2 to install a high plant density system and 20 to 100 EUR for maintaining the structure annually). Therefore, this topic remains particularly under-explored in the literature. Cost quantification is considered a complex task due to the multiple variables involved: type of vertical system, building height, supports and materials used, installation sites, climate conditions, technology requirements, and local incentives, among others. Two previous studies shed some light on this topic, showing that modular living walls often incur higher costs than green façades. Perini and Rosasco [97] conducted a cost–benefit analysis of different VGS, showing that the cost of a direct greening system ranges from 30 to 45 EUR/m^2, while the cost of a living wall system varies from 400 to 1200 EUR/m^2, depending on system and materials used. More recently, Manso et al. [98] showed that a green façade has an average installation and maintenance cost of 190 EUR/m^2 and 5.57 EUR/m^2, respectively, while a living wall has an average installation and maintenance cost of 750 EUR/m^2 and 18.98 EUR/m^2, respectively. The cost–benefit analyses of these solutions generally involve long to very long payback periods that could reach more than 50 years for modular living walls [97]. The provision of public subsidizing initiatives could be important to promote the installation of VGS.

Finally, while tangible benefits of VGSs such as temperature reduction, air quality improvement, energy saving, and noise abatement have been relatively well demonstrated, indirect health effects have not been analyzed fully. In the searched documents, health benefits were indirectly associated with the reduced exposure to air pollutants and noise and to the improved thermal comfort provided by these green solutions. However, the causal links between VGSs and measured health benefits in quantitative terms, for example, regarding medical consultations, hospital admissions, life years, mental disorders, or even reduced mortality, were not found within this review. Some plant species, mainly when used in indoor systems, may produce negative health outcomes due, for example, to allergens. These issues were not evaluated in the searched documents. Thus, a clear and measurable understanding of the complex relationship between health and VGS is still lacking in the literature.

The findings of this review have some limitations that should be emphasized. First, this review was limited to scientific papers published in English in two databases (Scopus and Web of Science). Thus, papers published in other languages, in other scientific repositories, or in other formats (thesis for example) were not evaluated. Second, the documents were selected according to the search rules described in the methodology, which probably excluded other relevant studies from the analysis. Third, due to the relatively high number of papers analyzed in this review, only the major findings were presented instead of adopting a meta-analysis in a comprehensive way.

5. Conclusions

Rapid urbanization is one of the major causes of increases in air pollution, noise, and urban heat, which are associated with various health and well-being impacts [17]. Urban green infrastructure is one of the most viable solutions to attenuate the impacts caused by urbanization on the quality of life of urban residents. Since the horizontal expansion of green spaces is difficult or even not possible in dense and compact cities, greening can only be developed vertically. Vertical greening can be considered a planning solution that helps to minimize the negative impacts of urbanization and improves the ecological performance of buildings. The development of VGS has become relatively easier and more flexible because plants can be attached to either the wall surface of buildings or other vertical structures and modules, either indoors or outdoors [99].

The review described in this paper was conducted to provide additional evidence on the effects of VGS on human health and well-being. Based on a review of 73 documents, this paper shows that the environmental and thermal benefits (improved air quality, enhanced building thermal comfort, and attenuated unwanted noise) associated with vertical greening were by far the most examined. Although these benefits could bring health and well-being outcomes, the most important gap identified within this review is the lack of studies measuring and quantifying the health and well-being benefits associated with VGSs. This is a relevant gap in the knowledge that should be addressed in the future. Other topics for future research identified within this review that may have health and well-being implications are (i) providing additional evidence about the role of VGSs in attenuating the urban heat island effect and on enhancing comfortable microclimate at the street level; (ii) evaluating the thermal contribution of VGSs during the winter, which is not consensual depending on the climate and the study; (iii) examining the role and benefits of indoor VGSs in-depth, which have been less analyzed than outdoor VGSs, for example, in terms of thermal comfort; (iv) conducting more research on physiological and psychological health and well-being associated with VGS by measurements and tests, as most of these studies have been supported by questionnaires; and (v) conducting more studies on the installation and maintenance costs of VGSs, which has not been analyzed fully and is often described as a barrier to the adoption of this infrastructure.

To sum up, by identifying the research trends, benefits, and knowledge gaps, this paper can help researchers to further evaluate the performance of outdoor and indoor VGSs on human health and well-being. It can be also helpful for promoting the adoption of these greening solutions, namely among planners and decision-makers to create healthy and more sustainable cities.

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References

1. Lin, D.; Sun, Y.; Yang, Y.; Han, Y.; Xu, C. Urban park use and self-reported physical, mental, and social health during the COVID-19 pandemic: An on-site survey in Beijing, China. *Urban For. Urban Green.* **2023**, *79*, 127804. [CrossRef] [PubMed]
2. Abhijith, K.; Kumar, P.; Gallagher, J.; McNabola, A.; Baldauf, R.; Pilla, F.; Broderick, B.; Di Sabatino, S.; Pulvirenti, B. Air pollution abatement performances of green infrastructure in open road and built-up street canyon environments: A review. *Atmos. Environ.* **2017**, *162*, 71–86. [CrossRef]
3. Martins, M.; Hadba, L.; Mendonça, P.; Silva, L. Evaluating the potential of vegetation to capture pollutants in urban environment. *Environ. Sci. Eng.* **2022**, *2*, 3–13. [CrossRef]
4. Silva, L.; Monteiro, J. The influence of urban form on environmental quality within a medium-sized city. *Procedia Eng.* **2016**, *161*, 2046–2052. [CrossRef]
5. Azkorra, Z.; Pérez, G.; Coma, J.; Cabeza, L.; Burés, S.; Álvaro, J.; Erkoreka, A.; Urrestarazu, M. Evaluation of green walls as a passive acoustic insulation system for buildings. *Appl. Acoust.* **2015**, *89*, 46–56. [CrossRef]
6. Silva, L.; Fonseca, F.; Rodrigues, D.; Campos, A. Assessing the influence of urban geometry on noise propagation by using the sky view factor. *J. Environ. Plan. Manag.* **2018**, *61*, 535–552. [CrossRef]
7. Koch, K.; Ysebaert, T.; Denys, S.; Samson, R. Urban heat stress mitigation potential of green walls: A review. *Urban For. Urban Green.* **2020**, *55*, 126843. [CrossRef]

8. Donovan, G. Including public-health benefits of trees in urban-forestry decision making. *Urban For. Urban Green.* **2017**, *22*, 120–123. [CrossRef]
9. Krellenberg, K.; Welz, J.; Reyes-Päcke, S. Urban green areas and their potential for social interaction—A case study of a socio-economically mixed neighbourhood in Santiago de Chile. *Habitat Int.* **2014**, *44*, 11–21. [CrossRef]
10. Aziz, N.; Shian, L.; Mokhtar, M.; Raman, T.; Saikim, F.; Chen, W.; Nordin, N. Effectiveness of urban green space on undergraduates' stress relief in tropical city: A field experiment in Kuala Lumpur. *Urban For. Urban Green.* **2021**, *63*, 127236. [CrossRef]
11. Vujcic, M.; Tomicevic-Dubljevic, J.; Zivojinovic, I.; Toskovic, O. Connection between urban green areas and visitors' physical and mental well-being. *Urban For. Urban Green.* **2019**, *40*, 335–343. [CrossRef]
12. Falco, A.; Piscitelli, P.; Vito, D.; Pacella, F.; Franco, C.; Pulimeno, M.; Ambrosino, P.; Arias, J.; Miani, A. COVID-19 epidemic spread and green areas Italy and Spain between 2020 and 2021: An observational multi-country retrospective study. *Environ. Res.* **2023**, *216*, 114089. [CrossRef] [PubMed]
13. De Meo, I.; Becagli, C.; Cantiani, G.; Casagli, A.; Paletto, A. Citizens' use of public urban green spaces at the time of the COVID-19 pandemic in Italy. *Urban For. Urban Green.* **2022**, *77*, 127739. [CrossRef]
14. Derks, J.; Giessen, L.; Winkel, G. COVID-19-induced visitor boom reveals the importance of forests as critical infrastructure. *For. Policy Econ.* **2020**, *118*, 102253. [CrossRef] [PubMed]
15. Silva, L.; Fonseca, F.; Pires, M.; Mendes, B. SAUS: A tool for preserving urban green areas from air pollution. *Urban For. Urban Green.* **2019**, *46*, 126440. [CrossRef]
16. Bustami, R.; Belusko, M.; Ward, J.; Beecham, S. Vertical greenery systems: A systematic review of research trends. *Build. Environ.* **2018**, *146*, 226–237. [CrossRef]
17. Ghazalli, A.; Brack, C.; Bai, X.; Said, I. Physical and non-physical benefits of vertical greenery systems: A review. *J. Urban Technol.* **2019**, *26*, 53–78. [CrossRef]
18. Aleksejeva, J.; Voulgaris, G.; Gasparatos, A. Assessing the potential for strategic green roof implementation for green infrastructure: Insights from Sumida ward, Tokyo. *Urban For. Urban Green.* **2022**, *74*, 127632. [CrossRef]
19. Rowe, T.; Poppe, J.; Buyle, M.; Belmans, B.; Audenaert, A. Is the sustainability potential of vertical greening systems deeply rooted? Establishing uniform outlines for environmental impact assessment of VGS. *Renew. Sustain. Energy Rev.* **2022**, *162*, 112414. [CrossRef]
20. Akram, M.; Hasannuzaman, M.; Cuce, E.; Cuce, P. Global technological advancement and challenges of glazed window, facade system and vertical greenery-based energy savings in buildings: A comprehensive review. *Energy Built Environ.* **2023**, *4*, 206–226. [CrossRef]
21. Chàfer, M.; Cabeza, L.; Pisello, A.; Tan, C.; Wong, N. Trends and gaps in global research of greenery systems through a bibliometric analysis. *Sustain. Cities Soc.* **2021**, *65*, 102608. [CrossRef]
22. Elsadek, M.; Liu, B.; Lian, Z. Green façades: Their contribution to stress recovery and well-being in high-density cities. *Urban For. Urban Green.* **2019**, *46*, 126446. [CrossRef]
23. Shao, Y.; Li, J.; Zhou, Z.; Zhang, F.; Cui, Y. The impact of indoor living wall system on air quality: A comparative monitoring test in building corridors. *Sustainability* **2021**, *13*, 7884. [CrossRef]
24. Fonseca, F.; Ribeiro, P.; Conticelli, E.; Jabbari, M.; Papageorgiou, G.; Tondelli, S.; Ramos, R. Built environment attributes and their influence on walkability. *Int. J. Sustain. Transp.* **2021**, *16*, 660–679. [CrossRef]
25. Wimalasooriya, C.; Licorish, S.; Costa, D.; MacDonell, S. A systematic mapping study addressing the reliability of mobile applications: The need to move beyond testing reliability. *J. Syst. Softw.* **2022**, *186*, 111–166. [CrossRef]
26. Norton, B.; Coutts, A.; Livesley, S.; Harris, R.; Hunter, A.; Williams, N. Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes. *Landsc. Urban Plan.* **2015**, *134*, 127–138. [CrossRef]
27. Currie, B.; Bass, B. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosyst.* **2008**, *11*, 409–422. [CrossRef]
28. Ottelé, M.; Van Bohemen, H.; Fraaij, A. Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecol. Eng.* **2010**, *36*, 154–162. [CrossRef]
29. Ottelé, M.; Perini, K.; Fraaij, A.; Haas, E.; Raiteri, R. Comparative life cycle analysis for green façades and living wall systems. *Energy Build.* **2011**, *43*, 3419–3429. [CrossRef]
30. Zhao, X.; Zuo, J.; Wu, G.; Huang, C. A bibliometric review of green building research 2000–2016. *Archit. Sci. Rev.* **2019**, *62*, 74–88. [CrossRef]
31. Abedi, S.; Yarahmadi, R.; Farshad, A.; Najjar, N.; Ebrahimi, H.; Soleimani-Alyar, S. Evaluation of the critical parameters on the removal efficiency of a botanical biofilter system. *Build. Environ.* **2022**, *212*, 108811. [CrossRef]
32. Anderson, V.; Gough, W. Harnessing the four horsemen of climate change: A framework for deep resilience, decarbonization, and planetary health in Ontario, Canada. *Sustainability* **2021**, *13*, 379. [CrossRef]
33. Andric, I.; Kamal, A.; Al-Ghamdi, S. Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: Case study of Qatar. *Energy Rep.* **2020**, *6*, 2476–2489. [CrossRef]
34. Caron, A.; Redon, N.; Thevenet, F.; Hanoune, B.; Coddeville, P. Performances and limitations of electronic gas sensors to investigate an indoor air quality event. *Build. Environ.* **2016**, *107*, 19–28. [CrossRef]
35. Chang, L.; Chang, F. Study of Living Wall Systems'(LWSs) Support system for improving LWSs Life cycle performance and noise reduction potential. *Build. Environ.* **2022**, *216*, 109007. [CrossRef]

36. Convertino, F.; Vox, G.; Schettini, E. Convective heat transfer in green façade system. *Biosyst. Eng.* **2019**, *188*, 67–81. [CrossRef]
37. Davis, M.; Tenpierik, M.; Ramírez, F.; Perez, M. More than just a green facade: The sound absorption properties of a vertical garden with and without plants. *Build. Environ.* **2017**, *116*, 64–72. [CrossRef]
38. De Lucia, M.; Treves, A.; Comino, E. Rice husk and thermal comfort: Design and evaluation of indoor modular green walls. *Dev. Built Environ.* **2021**, *6*, 100043. [CrossRef]
39. Feitosa, R.; Wilkinson, S. Small-scale experiments of seasonal heat stress attenuation through a combination of green roof and green walls. *J. Clean. Prod.* **2020**, *250*, 119443. [CrossRef]
40. Fensterseifer, P.; Gabriel, E.; Tassi, R.; Piccilli, D.; Minetto, B. A year-assessment of the suitability of a green façade to improve thermal performance of an affordable housing. *Ecol. Eng.* **2022**, *185*, 106810. [CrossRef]
41. Flores, S.; Filippín, C. Energy efficiency, thermal resilience, and health during extreme heat events in low-income housing in Argentina. *Energy Build.* **2021**, *231*, 110576. [CrossRef]
42. Ghazalli, A.; Brack, C.; Bai, X.; Said, I. Alterations in use of space, air quality, temperature and humidity by the presence of vertical greenery system in a building corridor. *Urban For. Urban Green.* **2018**, *32*, 177–184. [CrossRef]
43. Gunn, C.; Vahdati, M.; Shahrestani, M. Green walls in schools: The potential well-being benefits. *Build. Environ.* **2022**, *224*, 109560. [CrossRef]
44. Han, G.; Wen, Y.; Leng, J.; Sun, L. Improving comfort and health: Green retrofit designs for sunken courtyards during the summer period in a subtropical climate. *Buildings* **2021**, *11*, 413. [CrossRef]
45. He, C.; Qiu, K.; Pott, R. Reduction of traffic-related particulate matter by roadside plants: Effect of traffic pressure and sampling height. *Int. J. Phytoremed.* **2020**, *22*, 184–200. [CrossRef] [PubMed]
46. Hop, M.; Hiemstra, J. Contribution of green roofs and green walls to ecosystem services of urban green. *Acta Hortic.* **2013**, *990*, 475–480. [CrossRef]
47. Hozhabralsadat, M.; Heidari, A.; Karimian, Z.; Farzam, M. Assessment of plant species suitability in green walls based on API, heavy metal accumulation, and particulate matter capture capacity. *Environ. Sci. Pollut. Res.* **2022**, *29*, 68564–68581. [CrossRef]
48. Irga, P.; Pettit, T.; Irga, R.; Paull, N.; Douglas, A.; Torpy, F. Does plant species selection in functional active green walls influence VOC phytoremediation efficiency? *Environ. Sci. Pollut. Res.* **2019**, *26*, 12851–12858. [CrossRef]
49. Kazemi, F.; Rabbani, M.; Jozay, M. Investigating the plant and air-quality performances of an internal green wall system under hydroponic conditions. *J. Environ. Manag.* **2020**, *275*, 111230. [CrossRef]
50. Kyrkou, A. The role of greenery in healthcare facilities for children. *Sustain. Mediterr. Constr.* **2019**, *N9*, 8–12.
51. Li, Z.; Wang, Y.; Liu, H.; Liu, H. Physiological and psychological effects of exposure to different types and numbers of biophilic vegetable walls in small spaces. *Build. Environ.* **2022**, *225*, 109645. [CrossRef]
52. Liberalesso, T.; Júnior, R.; Cruz, C.; Matos, C.; Manso, M. Users' perceptions of green roofs and green walls: An analysis of youth hostels in Lisbon, Portugal. *Sustainability* **2020**, *12*, 10136. [CrossRef]
53. Mannan, M.; Al-Ghamdi, S. Life cycle embodied energy analysis of indoor active living wall system. *Energy Rep.* **2020**, *6*, 391–395. [CrossRef]
54. McCullough, M.; Martin, M.; Sajady, M. Implementing green walls in schools. *Front. Psychol.* **2018**, *9*, 619. [CrossRef] [PubMed]
55. Moghaddam, F.; Delgado, I.; Dominguez, E.; Mir, J.; Mateu, L. Understanding the performance of vertical gardens by using building simulation and its influences on urban landscape. *Archit. City Environ.* **2021**, *16*, 10321. [CrossRef]
56. Morgan, A.; Torpy, F.; Irga, P.; Fleck, R.; Gill, R.; Pettit, T. The botanical biofiltration of volatile organic compounds and particulate matter derived from cigarette smoke. *Chemosphere* **2022**, *295*, 133942. [CrossRef]
57. Ottelé, M.; Ursem, W.; Fraaij, A.; Van Bohemen, H. The development of an ESEM based counting method for fine dust particles and a philosophy behind the background of particle adsorption on leaves. *WIT Trans. Ecol. Environ.* **2011**, *147*, 219–230. [CrossRef]
58. Parhizkar, H.; Khoraskani, R.; Tahbaz, M. Double skin façade with Azolla; ventilation, indoor air quality and thermal performance assessment. *J. Clean. Prod.* **2020**, *249*, 119313. [CrossRef]
59. Paull, N.; Irga, P.; Torpy, F. Active green wall plant health tolerance to diesel smoke exposure. *Environ. Pollut.* **2018**, *240*, 448–456. [CrossRef]
60. Paull, N.; Krix, D.; Irga, P.; Torpy, F. Green wall plant tolerance to ambient urban air pollution. *Urban For. Urban Green.* **2021**, *63*, 127201. [CrossRef]
61. Pettit, T.; Irga, P.; Abdo, P.; Torpy, F. Do the plants in functional green walls contribute to their ability to filter particulate matter? *Build. Environ.* **2017**, *125*, 299–307. [CrossRef]
62. Pettit, T.; Irga, P.; Torpy, F. The in situ pilot-scale phytoremediation of airborne VOCs and particulate matter with an active green wall. *Air Qual. Atmos. Health* **2019**, *12*, 33–44. [CrossRef]
63. Pettit, T.; Irga, P.; Surawski, N.; Torpy, F. An assessment of the suitability of active green walls for NO_2 reduction in green buildings using a closed-loop flow reactor. *Atmosphere* **2019**, *10*, 801. [CrossRef]
64. Pettit, T.; Irga, P.; Torpy, F. The botanical biofiltration of elevated air pollution concentrations associated the Black Summer wildfire natural disaster. *J. Hazard. Mater. Lett.* **2020**, *1*, 100003. [CrossRef]
65. Pettit, T.; Torpy, F.; Surawski, N.; Fleck, R.; Irga, P. Effective reduction of roadside air pollution with botanical biofiltration. *J. Hazard. Mater.* **2021**, *414*, 125566. [CrossRef] [PubMed]
66. Pichlhöfer, A.; Sesto, E.; Hollands, J.; Korjenic, A. Health-related benefits of different indoor plant species in a school setting. *Sustainability* **2021**, *13*, 9566. [CrossRef]

67. Santiago, J.; Rivas, E.; Sanchez, B.; Buccolieri, R.; Esposito, A.; Martilli, A.; Vivanco, M.; Martin, F. Impact of different combinations of green infrastructure elements on traffic-related pollutant concentrations in urban areas. *Forests* **2022**, *13*, 1195. [CrossRef]
68. Scamoni, F.; Scrosati, C.; Depalma, M.; Barozzi, B. Experimental evaluations of acoustic properties and long-term analysis of a novel indoor living wall. *J. Build. Eng.* **2022**, *47*, 103890. [CrossRef]
69. Senosiain, J. Urban regreeneration: Green urban infrastructure as a response to climate change mitigation and adaptation. *Int. J. Des. Nat. Ecodyn.* **2020**, *15*, 33–38. [CrossRef]
70. Silva, C.; Serro, J.; Ferreira, P.; Teotónio, I. The socioeconomic feasibility of greening rail stations: A case study in Lisbon. *Eng. Econ.* **2019**, *64*, 167–190. [CrossRef]
71. Srbinovska, M.; Andova, V.; Mateska, A.; Krstevska, M. The effect of small green walls on reduction of particulate matter concentration in open areas. *J. Clean. Prod.* **2021**, *279*, 123306. [CrossRef]
72. Suárez-Cáceres, G.; Fernández-Cañero, R.; Fernández-Espinosa, A.; Rossini-Oliva, S.; Franco-Salas, A.; Urrestarazu, L. Volatile organic compounds removal by means of a felt-based living wall to improve indoor air quality. *Atmos. Pollut. Res.* **2021**, *12*, 224–229. [CrossRef]
73. Suárez-Cáceres, G.; Urrestarazu, L. Removal of volatile organic compounds by means of a felt-based living wall using different plant species. *Sustainability* **2021**, *13*, 6393. [CrossRef]
74. Talhouk, S.; Chalak, A.; Kamareddine, Z.; Fabian, M.; Itani, M.; Ferguson, N. Vertical gardening and Syrian women refugees in Lebanon: An exploratory study on motivation for gardening and depression relief. *Local Environ.* **2021**, *26*, 1235–1249. [CrossRef]
75. Tarboush, O.; Asilsoy, B.; Çağnan, Ç. Evaluation of perception with regards to green wall systems application in Nicosia, N. Cyprus. *Int. J. Adv. Appl. Sci.* **2020**, *7*, 24–36. [CrossRef]
76. Thorpert, P.; Rayner, J.; Haaland, C.; Englund, J.; Fransson, A. Exploring the integration between colour theory and biodiversity values in the design of living walls. *Front. Ecol. Evol.* **2022**, *10*, 804118. [CrossRef]
77. Tomson, N.; Michael, R.; Agranovski, I. Removal of particulate air pollutants by Australian vegetation potentially used for green barriers. *Atmos. Pollut. Res.* **2021**, *12*, 101070. [CrossRef]
78. Urbano-López, B. Greening, an urbanization coping mechanism. *Rev. Chapingo Serie Cienc. For. Ambiente* **2013**, *19*, 225–235. [CrossRef]
79. Urrestarazu, M.; Burés, S. Sustainable green walls in architecture. *J. Food Agric. Environ.* **2012**, *10*, 792–794.
80. Urrestarazu, L.; Blasco-Romero, A.; Fernández-Cañero, R. Media and social impact valuation of a living wall: The case study of the Sagrado Corazon hospital in Seville (Spain). *Urban For. Urban Green.* **2017**, *24*, 141–148. [CrossRef]
81. Urrestarazu, L.; Kaltsidi, M.; Nektarios, P.; Markakis, G.; Loges, V.; Perini, K.; Fernández-Cañero, R. Particularities of having plants at home during the confinement due to the COVID-19 pandemic. *Urban For. Urban Green.* **2021**, *59*, 126919. [CrossRef] [PubMed]
82. Van den Berg, A.; Wesselius, J.; Maas, J.; Tanja-Dijkstra, K. Green walls for a restorative classroom environment: A controlled evaluation study. *Environ. Behav.* **2017**, *49*, 791–813. [CrossRef]
83. Van den Bogerd, N.; Dijkstra, S.; Tanja-Dijkstra, K.; De Boer, M.; Seidell, J.; Koole, S.; Maas, J. Greening the classroom: Three field experiments on the effects of indoor nature on students' attention, well-being, and perceived environmental quality. *Build. Environ.* **2020**, *171*, 106675. [CrossRef]
84. Van Renterghem, T.; Hornikx, M.; Forssen, J.; Botteldooren, D. The potential of building envelope greening to achieve quietness. *Build. Environ.* **2013**, *61*, 34–44. [CrossRef]
85. Vera, S.; Viecco, M.; Jorquera, H. Effects of biodiversity in green roofs and walls on the capture of fine particulate matter. *Urban For. Urban Green.* **2021**, *63*, 127229. [CrossRef]
86. Yeom, S.; Kim, H.; Hong, T. Psychological and physiological effects of a green wall on occupants: A cross-over study in virtual reality. *Build. Environ.* **2021**, *204*, 108134. [CrossRef]
87. Yeom, S.; Kim, H.; Hong, T.; Ji, C.; Lee, D. Emotional impact, task performance and task load of green walls exposure in a virtual environment. *Indoor Air* **2022**, *32*, e12936. [CrossRef]
88. Wahba, S.; Kamel, B.; Nassar, K.; Abdelsalam, A. Effectiveness of green roofs and green walls on energy consumption and indoor comfort in arid climates. *Civ. Eng. J.* **2018**, *4*, 2284–2295. [CrossRef]
89. Weerakkody, U.; Dover, J.; Mitchell, P.; Reiling, K. Quantification of the traffic-generated particulate matter capture by plant species in a living wall and evaluation of the important leaf characteristics. *Sci. Total Environ.* **2018**, *635*, 1012–1024. [CrossRef]
90. Weerakkody, U.; Dover, J.; Mitchell, P.; Reiling, K. Topographical structures in planting design of living walls affect their ability to immobilise traffic-based particulate matter. *Sci. Total Environ.* **2019**, *660*, 644–649. [CrossRef]
91. Zhang, X.; Ni, Z.; Wang, Y.; Chen, S.; Xia, B. Public perception and preferences of small urban green infrastructures: A case study in Guangzhou, China. *Urban For. Urban Green.* **2020**, *53*, 126700. [CrossRef]
92. Zhu, Z.; Zhou, D.; Wang, Y.; Ma, D.; Meng, X. Assessment of urban surface and canopy cooling strategies in high-rise residential communities. *J. Clean. Prod.* **2021**, *288*, 125599. [CrossRef]
93. Zinia, N.; McShane, P. Ecosystem services management: An evaluation of green adaptations for urban development in Dhaka, Bangladesh. *Landsc. Urban Plan.* **2018**, *173*, 23–32. [CrossRef]
94. Živković, P.; Dimitrijević-Jovanović, D.; Stevanović, Ž. The impact of the building envelope with the green living systems on the built environment. *Therm. Sci.* **2018**, *22*, 1033–1045. [CrossRef]

95. Dahanayake, K.; Chow, C. Studying the potential of energy saving through vertical greenery systems: Using EnergyPlus simulation program. *Energy Build.* **2017**, *138*, 47–59. [CrossRef]
96. Jim, C.; Hui, L.; Rupprecht, C. Public perceptions of green roofs and green walls in Tokyo, Japan: A call to heighten awareness. *Environ Manag.* **2022**, *70*, 35–53. [CrossRef]
97. Perini, K.; Rosasco, P. Cost–benefit analysis for green façades and living wall systems. *Build. Environ.* **2013**, *70*, 110–121. [CrossRef]
98. Manso, M.; Teotónio, I.; Silva, C.; Cruz, C. Green roof and green wall benefits and costs: A review of the quantitative evidence. *Renew. Sust. Energ. Rev.* **2021**, *135*, 110111. [CrossRef]
99. Ling, T.; Chiang, Y. Well-being, health and urban coherence-advancing vertical greening approach toward resilience: A design practice consideration. *J. Clean. Prod.* **2018**, *182*, 187–197. [CrossRef]