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Green walls and health: An umbrella review

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ABSTRACT

Current societal challenges like climate change led to a general agreement that our cities need to become greener and our lifestyles more sustainable. This transformation of our daily living environments can also impact the prevalence of non-communicable diseases as a global disease burden of our time. These positive impacts of horizontal green spaces on human health are widely recognized. However, it is still unclear whether the same is true for green walls, as a promising nature-based solution for dense urban spaces which is increasingly applied. To date, the available research on green walls has not been systematically synthesized along the potential impact pathways of reducing environmental stressors (Mitigation), restoring capacities (Restoration), and promoting healthier behavior (Instoration). We conducted a systematic review of 30 reviews to synthesize available evidence on all three pathways and direct health outcomes, following the established strategies of PICOS and PRISMA. We assessed the review quality through AMSTAR. We found strong consistent evidence that green walls can mitigate urban heat island effects (daylight surface temperature: -0.3 °C to -31.9°, daylight air temperature: -0 °C to -8.7 °C), air pollution (PM2.5: -25% to -99%, PM10: -23% to -60%), and noise pollution (sound pressure level: -1dBA to -5dBA). We found some evidence for disaster risk reduction and restoration effects. There were no reviews on the instoration pathway or direct health outcomes. The underlying reviews rated low according to the AMSTAR checklist, which might limit our findings. We recognize a generally young research field and conclude that more in-field studies are needed in all pathways to better understand the relationship between green walls and health.

1. Introduction

In recent years, the qualitative (re)design of the human habitat has become a central and concrete field of action in important political agendas at the national and international level with the United Nations Sustainable Development Goals as its frontrunner [1]. In addition, Europe is massively funding the concept of nature-based solutions (NBS) as a holistic approach to tackle multiple societal challenges from climate change mitigation and climate resilience of urban environments to the health and wellbeing of their citizens [2,3]. Specifically, the health-environment context is getting more and more into the spotlight with the current global disease burden being dominated by Non-Communicable-Diseases (NCD) such as diabetes, obesity, chronic respiratory diseases, cancer, and mental and cardiovascular disorders, which are thought to be related to the environmental conditions of their residents [4,5]. For example, it has been widely confirmed that green spaces in general can make an important contribution to mitigating this disease burden [6]. Accordingly, some hope is also placed on green walls (GW) as a nature-based solution in dense urban areas to show similar positive health effects. Green walls, along with green roofs, are often the only way to integrate nature in the city, especially where street space is too narrow for trees. Thus, if GW would be able to positively influence health outcomes, the predominantly bare walls in our urban areas present a huge potential to be covered by greenery to improve public health. To build green walls (or vertical greenery systems, vegetated facades, or vertical gardens) two systems are widely used. Green facades as the traditional system use vegetation species that root in the ground and climb the facade, whether directly on the wall or indirectly on a sub-structure. Living walls are a more technical solution where carrier systems are used to grow plants in a substrate vertically along the building envelope, usually integrating irrigation and drainage systems.

However, it is still largely unclear whether and to what extent the positive evidence of horizontal green spaces on health can be transferred to the vertical green spaces on GW. Potential mechanistic pathways between GW and health include mitigating environmental stressors (Mitigation), restoring capacities and reducing stress (Restoration), and

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fostering healthy behavior (Instoration), as they have been established for green spaces [7]. Considering that green walls are a relatively new tool for the green transformation of cities and have attracted research interest in the last few years, it is important to synthesize available knowledge.

The aim of this umbrella review (or review of reviews) is to provide a systematic overview of the available evidence on green walls and health from a wide range of disciplines, as the scientific literature, and thus reviews, on this topic have increased substantially in recent years. Our goal is to summarize what is known about the possible pathway mechanisms between green walls and health. We will then compare these findings with the state of research on green spaces in order to identify potential research gaps. Lastly, we aim to support the development of this young multidisciplinary field by cross-referencing between disciplines and drawing attention to the versatility of the potential positive effects of green walls on health.

2. Methods

For this review, we use the global term GW which is less technical but semantically equivalent to vertical greenery systems (VGS) which reflects the facade engineering origin. As a potential interdisciplinary field of research, it is important to use easy and precise terms, which can be understood by other disciplines. In addition, the term green wall pares up with the terms green roofs and green space. It is necessary however to distinguish two types of green walls (see Fig. 1). Living walls (LW, right image) are carrier systems with substrate attached to the wall, while traditional green facades (GF, left image) root in the ground and climb on the wall. These two systems are composed of different sub-categories but their differentiation seems neglectable for this umbrella review. For further details on these sub-categories, we refer to Bustami et al. 2018 [8] or Yan et al. 2022 [9].

2.1. Search strategy

We conducted this umbrella review following the PRISMA reporting guidelines [10] (Table S1). The search string was constructed through the PICOS approach and contained blocks of the theorized health pathways of mitigation, restoration, and instoration as well as for health outcomes (Table S2). In addition, results were restricted to reviews and had to be written in English. There was no restriction by year of publication. The search for reviews was carried out in the three databases Scopus, Web of Science, and PubMed in August 2022.

2.2. Study selection

In order to be included in this umbrella review the included reviews had to explicitly report on green walls and health outcomes or associated pathways (mitigation, restoration, instoration) in outdoor environments. Thus, reviews focusing exclusively on indoor spaces or green roofs were excluded. Authors A1 and A2 independently screened the review articles at every stage and resolved discrepancies by discussion. We retrieved 142 reviews from the three databases in total. After reducing duplicates, 86 reviews remained. The abstracts of the remaining review articles were screened for the eligibility criteria (Table S3). This left 48 articles eligible for full-text access. Of these 48 reviews, 20 were excluded because they were not explicit about green walls and/or health outcomes or associated pathways (Table S4). One eligible study was identified through snowballing, and another was known to the authors. The final list included 30 reviews (Fig. 2).

2.3. Data extraction

A data extraction sheet was created to organize information related to the author, year, journal, main findings, review type, and the amount, types, and locations of studies included, as well as the definition of green walls, and the evidence on health outcomes and associated pathways (overview in Table 1, detailed information in Tables 2-8). If reported, we extracted findings from included reviews by quantitative values (mean, min, max). In addition, we categorized the level of reported evidence by the direction of the effect (positive, negative, mixed) and by the amount and type of underlying studies (strong, medium, low and unexplicit evidence, theorized links; see Table 1 for evaluation criteria). We did not conduct any meta-analysis since multiple reviews will likely be based partly on the same studies, leading to a biased result. The data extraction was performed in duplicate by authors A1 and A2. Any discrepancies were resolved by discussion.

2.4. Quality assessment

We assessed the methodological quality of the reviews with the help of the AMSTAR 2 checklist [39] which is a common tool in health

Fig. 1. Left: Green facade in Palaisstraße, Detmold, Germany; Right: Living wall at Museu Coleção Berardo, Lisbon, Portugal.

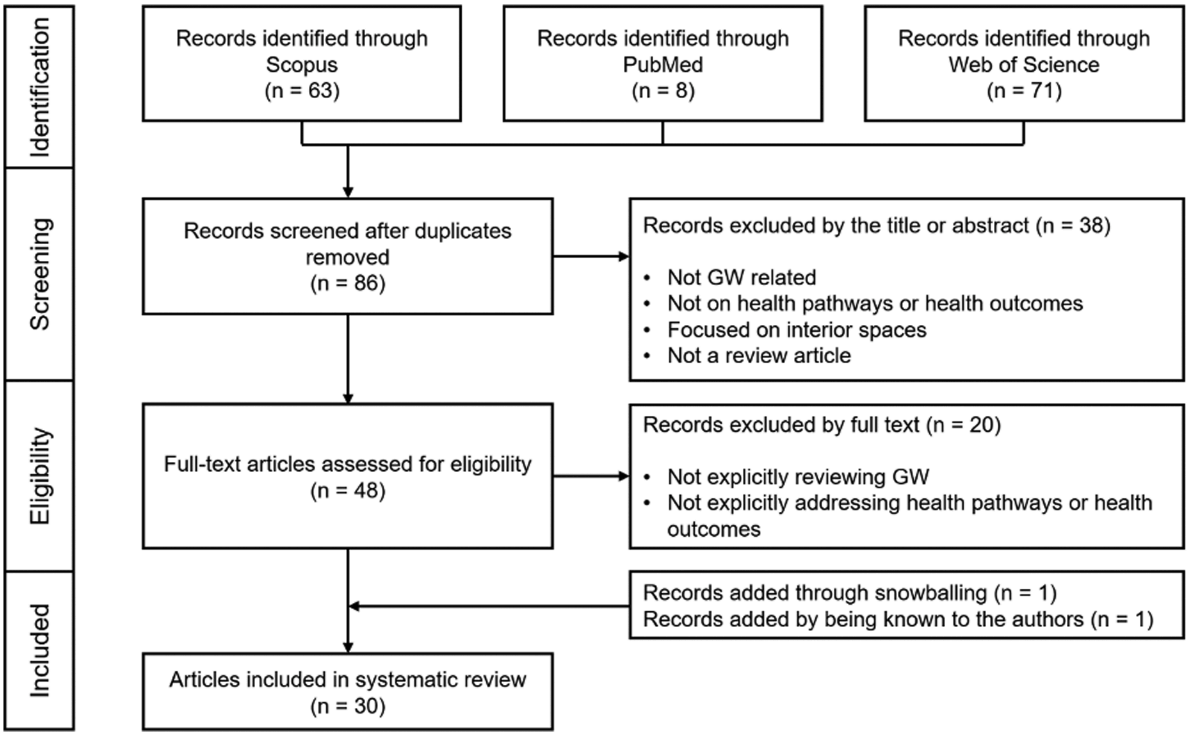

Fig. 2. Flow diagram of the selection process of review articles.

sciences, but rarely used in the fields of architecture and engineering. We acknowledged the different disciplinary origins and adjusted the following items accordingly:

- Item 2 "*Did the report of the review contain an explicit statement that the review methods were established prior to the conduct of the review and did the report justify any significant deviations from the protocol?*": We did not assess registered study protocols for full points.
- Item 3 "*Did the review authors explain their selection of the study designs for inclusion in the review?*": We skipped this item since the mentioned study designs are not conducted in this research field.
- Item 4 "*Did the review authors use a comprehensive literature search strategy?*": We adapted the checklist partly by skipping the assessment of study registries and expert consultation since it is very uncommon to do so in this research field.
- Item 7 "*Did the review authors provide a list of excluded studies and justify the exclusions?*": We changed the item to noncritical since it is not a common practice outside of health sciences, especially in engineering.
- Item 8 "*Did the review authors describe the included studies in adequate detail?*": We simplified the item. A "yes" was given when the review included detailed tables about the involved studies.
- Item 10 "*Did the review authors report on the sources of funding for the studies included in the review?*": We skipped this item because the funding source of the studies is not as sensitive in this field of research.
- Item 15 "*If they performed quantitative synthesis did the review authors carry out an adequate investigation of publication bias (small study bias) and discuss its likely impact on the results of the review?*": We dropped this item because of its limited applicability in this research field.

Quality Assessment was performed in duplicate, and discrepancies were resolved via discussion. Results can be viewed in supplementary material Table S5.

3. Results

Our umbrella review included 30 reviews of which the vast majority focused on the mitigation pathway (Table 1). All reviews were published between 2014 and 2022 and increased to 5–8 reviews per year in the last 3 years (Fig. 3a), demonstrating the young research field of green walls and health. In line with these findings, we observed heterogeneity in the wording. While the global term green wall (GW) is the most common, still about half of the reviews use different terms (Fig. 3b). In addition, we observed that only 26,7% of the reviews were truly systematic following the PRISMA guidelines, although some systematization was found in 33,3% of the reviews. Thus, 40% of the reviews were purely narrative, making it difficult to extract relevant data (Fig. 3c). This is congruent with the disciplinary origin of the reviews being dominantly in architectural & engineering fields (Fig. 3d), where these systematic approaches to review are not as common as in health sciences. In line with these observations, the review quality according to the AMSTAR 2 protocol [39] was very low on average, generally missing to meet the critical domains necessary to receive a higher score, although it was adapted to the field (see Section 2.4 for detailed information, see Table S4 for detailed ratings). Together these general observations provide a frame to evaluate the level of evidence of the upcoming research findings correctly.

3.1. *Pathway mitigation*

3.1.1. *Urban heat island*

Potential effects of GW to mitigate heat in urban areas were most common in the included reviews. 21 out of 30 reviews included studies about heat mitigation showing a homogenous trend towards a positive effect on the heat mitigation of GW (Table 2). According to these reviews, GW reduced the air temperature by 0 °C to −8.7 °C during the day and −0.1 °C to −3.7 °C during the night. Surface temperature mitigation was generally found to have a stronger effect with −0.3 °C to −31.9 °C during the day and +2.0 °C to −6.0 °C during the night. Two studies made the effort to calculate mean temperature reduction. Koch et al.

Table 1
Summary of included studies (n = 30) in alphabetical order.

Nr	Author	Year	Review method	Studies included	Mitigation Pathway					Instoration Pathway			Restoration Pathway			Health Outcomes								
					AP	NP	UHI	DRR	LP	PA	SA	DH	S	EC, WB	IS	MH	M	CV	O	C	D	R	BO	GH
[11]	Abhijith et al.	2017	NR	n/a	+ *																			
[12]	Aflaki et al.	2017	NR	n/a			+ *																	
[13]	Al-Kayiem et al.	2020	NR	n/a			+ ***							>										
[14]	Antoszewski et al.	2020	SR (n/a)	173 (59 GW)			+ **																	
[15]	Ascione et al.	2020	SR (n/a)	95		+ *	+ ***																	
[16]	Balderrama et al.	2022	SR	40 (6 on GW)		+ **								>										
[17]	Besir & Cuce	2018	NR	n/a			+ ***	+ *																
[8]	Bustami et al.	2018	SR	166	+ **	+ **	+ *	0 *																
[18]	Charoenkit & Yiemwattana	2016	SR (n/a)	23	+ *		+ ***	+ *																
[19]	Corada et al.	2021	SR	62 (5 GW)	+ (*)																			
[20]	Ghazalli et al.	2019	SR (n/a)	108		+ **	+ (*)			>			+ *	+ *		>		>						>
[21]	Goel et al.	2022	SR (n/a)	60	+ *	+ *	+ *	+ *			>		+ *			>								
[22]	Hunter et al.	2014	NR	28			+ (*)																	
[23]	Karimi et al.	2022	SR (n/a)	91 (20 on GW)			+ *																	
[24]	Koch et al.	2020	NR	n/a			+ ***																	
[25]	Medl et al.	2017	SR	11			+ ***																	
[26]	Ode Sang et al.	2022	SR (n/a)	69 (+11 reviews)	+ ***	+ (*)	+ (*)	>					>	+ *		>	>	>				>	>	>
[27]	Oquendo-Di Cosola et al.	2022	SR (n/a)	40		+ ***	+ ***																	
[28]	Pacini A et al.	2022	NR	n/a	+ *		+ *	+ *					+ *	>	>	>		>						
[29]	Radic et al.	2019	SR	73 (+1 PhD, +19 gray literature)	+ **	+ ***	+ ***	+ **			>		+ *	+ **										
[30]	Susca et al.	2022	SR	38			+ ***																	
[31]	Taleghani	2018	NR	3			+ *																	
[32]	Tomson et al.	2021	SR	13	+ ***			+ *																
[33]	van Renterghem et al.	2015	NR	n/a		+ *																		
[34]	Wong et al.	2021	SR (n/a)	30 GW			+ ***							>										
[35]	Wróblewska & Jeong	2021	NR	n/a	+ (*)																			
[9]	Yan et al.	2022	SR (n/a)	27 (+ 7 Reviews)		+ ***																		
[36]	Yang & Jeon	2020	SR	70 (3 on GW)		+ **								+ *		>								>
[37]	Yenneti et al.	2020	NR	n/a (2 on GW)			+ *																	
[38]	Ysebaert et al.	2021	NR	n/a	+ (*)																			

Notes: Review method: NR = Narrative review; SR = systematic review; SR (n/a) = Systematic review without guidelines / Evidence; Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes; AP = Air Pollution; NP = Noise Pollution; UHI = Urban Heat Island; DRR = Disaster Risk Reduction; LP = Light Pollution; PA = Physical Activity; SA = Social Activity; DH = Diet; *S* = Stress; EC, WB = Environmental Comfort, well-being; IS = Immune System; MH = Mental Health; *M* = Mortality; CV = Cardiovascular-related; *O* = Obesity-related; C = Cancer; *D* = Diabetis; *R* = Respiratory-related; BO = Birth Outcomes; GH = General health.

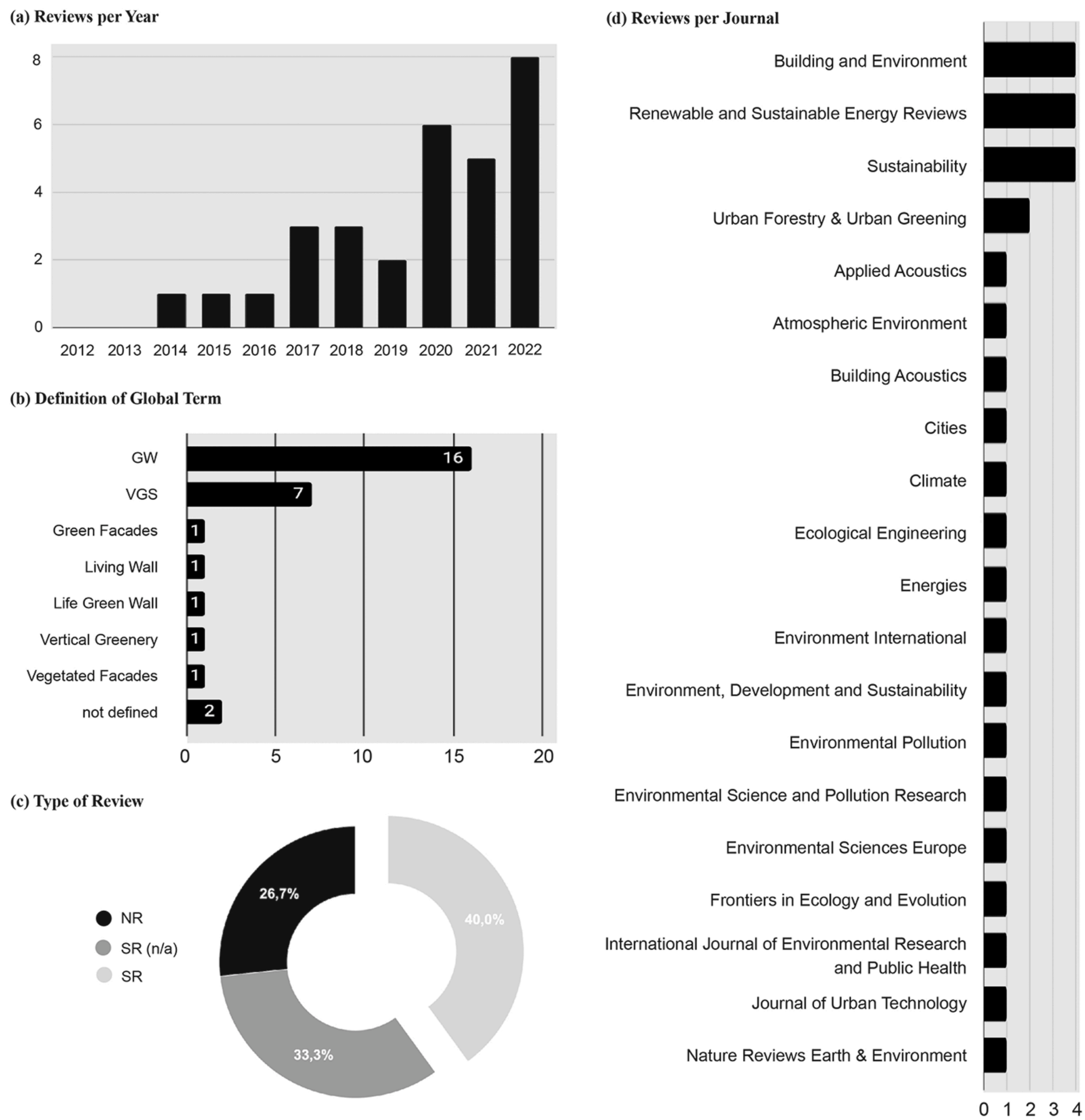

Fig. 3. Descriptive statistics by (a) reviews per year; (b) definition of global term; (c) type of review; (d) reviews per journal; Review method: NR = Narrative review; SR = systematic review; SR (n/a) = Systematic review without guidelines/Evidence.

[24] focused on GW systems and reported means of −8 °C for direct GF, −9 °C for indirect GF, and −10 °C for LW. Wong et al. [34] reported means of a 3 °C reduction in air temperature and a 16 °C reduction in wall surface temperature. In line with these findings, Oquendo-Di Cosola reported a declining effect size the greater the distance from the wall [27], although only a few underlying studies reported the distance of the temperature sensor from the wall. The reported wide range of effects can be partly explained by the range of external conditions and differences within green wall properties.

There are a variety of external and internal factors reported that influence the performance of green walls in heat mitigation, with the climate zone being dominant [30]. To distinguish climate zones the Köppen classification was frequently used. Current evidence suggests that green walls perform best during hot summers in Mediterranean climate zones with a mean surface temperature reduction of 16 °C [24]. The least reduction was reported by Koch et al. in monsoon-influenced humid subtropical climates with a surface temperature reduction of 5 °C during summer [24]. In addition, the orientation of the green wall relative to the sun and seasonality seem to impact the performance of green walls [30,34]. Furthermore, the density of the urban fabric can potentially modify the effect by interrupting direct radiation [18,30,34]. Additionally, classic facades lose a lot of their stored heat of the day, while green walls tend to stay at a more constant surface temperature during the night, but not heating up in the first place [34]. In line with those findings, Susca et al. found heterogeneous results in cooling night surface temperature in different climate zones, which might be explainable by a high leaf area index (LAI) that prevents heat dissipation [30]. In the morning the thickness of leaves and the thickness of the general vegetation layer might also delay the rise of ambient temperature [14]. High foliage and LAI relate to the shading capacity of green walls on the wall surface, while the vegetation type is reported to be related to the evapotranspiration process of the plants [27,34]. Thus, the choice of GW system (LW or GF) influences the performance [18,24]. LW generally perform better in cooling the surface temperature due to the substrate as an additional protection layer, compared to GF [27,34]. Additional external effect modifiers include the window-to-wall ratio [34] and the color and material of the bare wall that is compared to the green wall performance might influence measured results since

Table 2
Evidence on heat mitigation.

Nr	Author	Year	Review method	Number of studies on the topic (empirical/ total)	Studies categorized by	Evidence	Air Temperature		Surface Temperature	
							Daytime mean (min, max)	Nighttime mean (min, max)	Daytime mean (min, max)	Nighttime mean (min, max)
[13]	Al-Kayiem et al.	2020	NR	17/19	–	+ ***	- (-, -)	- (-, -)	d GF - (−0.5 °C, −16.0 °C) id GF - (1.0 °C, −16.4 °C)	- (-, -)
[15]	Ascione et al.	2020	SR (n/a)	13/13	city and climate zone	+ ***	- (-, -)	- (-, -)	- (−1.6 °C, −30.0 °C)	- (+2.0 °C, −1.9 °C)
[17]	Besir & Cuce	2018	NR	31/34	country	+ ***	- (-, -)	- (-, -)	d GF - (−1.2 °C, −16.0 °C) id GF - (1.0 °C, −16.4 °C) LW - (−1.0 °C, −31.9 °C)	- (-, -) - (-, -) LW - (−2.0 °C. −6.0 °C)
[18]	Charoenkit & Yiemwattana	2016	SR (n/a)	12/12	climate zone and country	+ ***	- (-, -)	- (-, -)	- (−0.3 °C, −30.0 °C)	- (-, -)
[24]	Koch et al.	2020	NR	50/50	country	+ ***	d GF - (−2.1 °C, −3.0 °C) id GF -(-, -) LW - (-, -)	- (-, -)	d GF −8 °C (−1.5 °C, −26 °C) id GF −9 °C (−3 °C, −17 °C) LW −10 °C (−2 °C, −30 °C)	d GF - (-, -) id GF -(+2 °C, +3.5 °C) LW - (-, -)
[25]	Medl et al.	2017	SR	11/11	country and climate zone	+ ***	- (-, -)	- (-, -)	- (−5.0 °C, −31.9 °C)	- (-, -)
[27]	Oquendo-Di Cosola et al.	2022	SR (n/a)	25/25	climate zone	+ ***	- (−0.8 °C, −8.7 °C)	- (-, -)	- (−0.3 °C, −31.9 °C)	- (-, -)
[29]	Radic et al.	2019	SR	28/28	climate zone	+ ***	- (0 °C, −3.3 °C)	- (-, -)	- (-, -)	- (-, -)
[30]	Susca et al.	2022	SR	38/38	climate zone	+ ***	- (−0.1 °C, −4.8 °C)	- (−0.1 °C, −3.7 °C)	- (−2.1 °C, −17.5 °C)	- (+2.0 °C, −2.1 °C)
[34]	Wong et al.	2021	SR (n/a)	30/30	city	+ ***	−3 °C (−2 °C, −4 °C)	- (-, -)	−16 °C (−10.7 °C, −18.8 °C)	- (-, -)
[14]	Antoszewski et al.	2020	SR (n/a)	2/59	country	+ **	-(-, −1.0 °C)	- (-, -)	- (-, −12 °C)	- (-, -)
[12]	Aflaki et al.	2017	NR	1/2	city and country	+ *	- (-, −1.0 °C)	- (-, -)	- (−4.0 °C, −12 °C)	- (-, -)
[8]	Bustami et al.	2018	SR	1/76	country	+ *	- (-, -)	- (-, -)	- (−4.4 °C, −11.6 °C)	- (-, -)
[21]	Goel et al.	2022	SR (n/a)	2/2	city and country	+ *	- (-, -)	- (-, -)	- (−3.3 °C, −11.6 °C)	- (-, -)
[23]	Karimi et al.	2022	SR (n/a)	2/3	climate zone	+ *	- (−1.9 °C, −3.0 °C)	- (-, -)	- (−8.7 °C, −9.9 °C)	- (-, -)
[28]	Pacini et al.	2022	NR	n/a	–	+ *	- (-, -)	- (-, -)	- (-, -)	- (-, -)
[31]	Taleghani	2018	N	3/3	city	+ *	- (0 °C, −3.3 °C)	- (-, -)	- (−4.4 °C, - 5.8 °C)	- (-, -)
[37]	Yenneti et al.	2020	N	2/2	country	+ *	- (−0.3 °C, −1.5 °C)	- (-, -)	- (-, -)	- (-, -)
[20]	Ghazalli et al.	2019	S (n/a)	0/24	continent	+ (*)	- (-, -)	- (-, -)	- (-, -)	- (-, -)
[22]	Hunter et al.	2014	N	n/a	city and country	+ (*)	- (-, -)	- (-, -)	- (-, -)	- (-, -)
[26]	Ode Sang et al.	2022	S (n/a)	0/2	–	+ (*)	- (-, -)	- (-, -)	- (-, -)	- (-, -)

Notes: Review method: NR = Narrative review; SR = systematic review; SR (n/a) = Systematic review without guidelines / Evidence Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes.

dark-colored walls heat up more because of their lower albedo effect [14]. Therefore a large part of the reported heterogeneity in the results might be attributed to the variety of external conditions and different green wall setups used. Lastly, we observed a low review quality that might partly explain the wide effect ranges of GW to mitigate urban heat island effects.

3.1.2. Air pollution

From 30 included reviews, 11 dealt with the potential of GW to mitigate air pollution. All reviews found at least some evidence that GW are able to reduce particulate matter (PM2.5 and PM10) and gaseous pollutants (NO_2 and SO_2) as shown in Table 3. For PM2.5 reductions between 20.2% and 99.0% were found. PM10 could be reduced by 23% up to 60%. NO_2 was reduced by 15.0% up to 64.5%. GF net removal rate (s^{-1}) for SO_2 ranged from 1.05×10^{-6} to 1.11×10^{-6} in one study [40] reported by Thomson et al. [32]. The reported wide range of effects is partly explained by external conditions and differences in vegetation species.

A large part of the heterogeneity in the reported effect sizes can be explained through the general mechanisms of GW air pollution mitigation that have been reported in the reviews. Firstly, PM is temporarily deposited on leaf surfaces [32], which makes species with a higher leaf area index (LAI) perform better [29]. Secondly, PM might be dispersed through vegetation with the help of rainfall [32], which relates its

Table 3
Evidence on air pollution mitigation.

Nr	Author	Year	Review method	Number of studies on the topic (empirical/ total)	Studies categorized by	Evidence	PM2.5 mean (min, max)	PM10 mean (min, max)	NO_2 mean (min, max)	SO_2 removal rate (s^{-1}) mean (min, max)
[26]	Ode Sang et al.	2022	SR (n/a)	8/10	–	+ ***	- (−25.0%, −99.0%)	- (-, 37%)	- (-, -)	- (-, -)
[32]	Tomson et al.	2021	SR	8/13	city	+ ***	- (-, -)	- (−23%, −50%)	- (−15%, −35%)	- (1.05×10^{-6}, 1.11×10^{-6})
[8]	Bustami et al.	2018	SR	1/5	country	+ **	- (-, -)	- (-, -)	- (-, -)	- (-, -)
[29]	Radic et al.	2019	SR	5/8	climate zone	+ **	- (−45.3%, −71.4%)	- (-,−23%)	- (-,−15%)	- (-,-)
[11]	Abhijith et al.	2017	NR	1/1	–	+ *	- (-, -)	- (-,50%)	- (-, 35%)	- (-, -)
[18]	Charoenkit & Yiemwattana	2016	SR (n/a)	n/a	climate zone and country	+ *	- (-,-)	- (-,-)	- (-,-)	- (-,-)
[21]	Goel et al.	2022	SR (n/a)	1/1	city and country	+ *	- (−20.2%, −34.2%)	- (−23.7%, −47.3%)	- (−31.6%, −64.5%)	- (-, -)
[28]	Pacini et al.	2022	NR	1/2	–	+ *	- (-, -)	- (-, -)	- (-, -)	- (-, -)
[19]	Corada et al.	2021	SR	0/5	country	+ (*)	- (-, -)	- (-, -)	- (-, -)	- (-, -)
[35]	Wróblewska & Jeong	2021	NR	n/a	–	+ (*)	- (-,-)	-(-, −60%)	- (-,-)	- (-,-)
[38]	Ysebaert et al.	2021	NR	0/5	–	+ (*)	- (-,-)	- (-,-)	- (-,-)	- (-,-)

Notes: Review method: NR = Narrative review; SR = systematic review; SR (n/a) = Systematic review without guidelines / Evidence Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes.

effectiveness to the local meteorological conditions. This wash-off by rainfall worked significantly better for larger particle sizes (PM10) than smaller ones [38], which are associated with much more harm to human health [26]. Thirdly, PM mitigation might differ not only by species but also by residence time [38]. Fourthly, external factors likely modify the effectiveness of GW. Urban geometry, the GW location, the greening ratio, the original pollution level, and wind speed were reported to modify the effect [26,32]. Lastly, there are also feedback effects considered, although inconclusive, since the vegetation might be damaged through the uptake of PM hindering its ability to mitigate further air pollution [26]. Differences in PM removal could not be attributed to the microstructure of vegetation species (grooves, ridges stomata, and trichomes) [38]. In contrast to PM removal, gasses are uptaken through leaf stomata, with differences in capacity between species that explain the reported range of mitigation [32]. No difference between LW and GF has been reported, although there seems more potential in LW since more species with high LAI are available and substrates that might capture pollutants temporarily. Additionally, heterogeneous study designs and rather low observed review quality may play a role in the reported wide effect range.

3.1.3. Noise pollution

The influence of green walls on the acoustic environment in outdoor spaces was studied in 11 out of 30 reviews. Consistent positive evidence of noise mitigation was found (Table 4). Six reviews reported reductions in sound pressure level (SPL) in decibels (dB) or A-weighted decibels (dBA or dB(A)) and four reviews mentioned reverberation time (the time required for the sound pressure level to decrease by a given amount of dB after the sound source has stopped). The potential of GW to mitigate noise ranged from −1 dB to −10 dB. However, the study designs reported different experimental setups leading to different results. Among the six reviews that explicitly reported sound reductions, three [15,27,29] included the empirical study of Wong et al. [41] where eight different GW were set up in a park in Singapore in order to study insertion loss (the difference, in dB, between the sound pressure level before and after a sound-attenuating object), leading to maximum mitigation of 10 dB. However, the experimental setup located the sound source and the receiving microphones on different sides of the green wall. This differs from the setups in the other three reviews [9,16,33] which considered only studies with the sound source and the receiver in street environments, reporting maximum mitigation of up to −5 dBA in simulation studies. Thus, the noise mitigation effect at the street level of

Table 4
Evidence on noise mitigation.

Nr	Author	Year	Review method	Number of studies on the topic (empirical/total)	Studies categorized by	Evidence	SPL difference mean (min, max)	Reverberation time
[27]	Oquendo-Di Cosola et al.	2022	SR (n/a)	4/12	climate zone	+ ***	- (−2 dB, −10 dB)	>
[29]	Radic et al.	2019	SR	7/12	climate zone	+ ***	- (−1 dB, −10 dB)	–
[9]	Yan et al.	2022	SR (n/a)	5/34	–	+ ***	- (−1.6 dB, −3.4 dB)	>
[16]	Balderrama et al.	2022	SR	2/6	country	+ **	- (−2 dBA, −5 dBA)	>
[8]	Bustami et al.	2018	SR	3/5	country	+ **	- (-, -)	–
[20]	Ghazalli et al.	2019	SR (n/a)	3/9	continent	+ **	- (-, -)	–
[36]	Yang & Jeon	2020	SR	3/5	–	+ **	- (-, -)	–
[15]	Ascione et al.	2020	SR (n/a)	3	city and climate zone	+ *	- (−2 dB, −10 dB)	–
[21]	Goel et al.	2022	SR (n/a)	n/a	city and country	+ *	- (-, -)	–
[33]	van Renterghem et al.	2015	NR	n/a	–	+ *	- (−1 dBA, −4.4 dBA)	>
[26]	Ode Sang et al.	2022	SR (n/a)	0/3	–	+ (*)	- (-, -)	–

Notes: Review method: *N* = Narrative review; *S* = systematic review; S (n/a) = Systematic review without guidelines / Evidence Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes.

green walls seems to be more likely between −1 and −5 dBA. Therefore, the study design can partly explain the observed effect range.

The noise mitigation potential of green walls depends on two main factors: First, internal factors are referred to the properties of the green wall, from which sound absorption is among the most relevant considerations. The absorption coefficient of plants is predominantly defined by the leaf area density and angle of leaf orientation [15] and performs best in the high-frequency range [9]. Additionally, the soil substrate and moisture content of living walls significantly influence the absorption coefficient [9,15,20,27,33]. Aside from sound absorption, the reflection characteristics (how the sound is reflected) also influence acoustic performance [9,42,43]. Then, external contextual factors also determine the mitigation potential of GWs, including the geometry and materials of the surrounding built environment, the characteristics of the sound sources, receivers, and the atmospheric (meteorological) conditions [16]. As indicated by van Renterghem et al. [33], meteorological effects strongly affect sound propagation outdoors. Under realistic outdoor conditions factors such as atmospheric refraction of sound can occur (i.e. curving of sound paths due to temperature profiles and wind). Thus, the limited number of studies in-field and the rather low review quality may affect the reported effect range.

3.1.4. Disaster risk reduction

From the 30 reviews, eight looked at potential effects of GW to mitigate disaster risks like climate change and associated extreme weather events like heavy rainfall (Table 5). First, Carbon dioxide (CO_2) mitigation by green walls was reviewed by 5 studies. But all referred only to one single pioneer modeling study by Marchi et al. 2015 [40] which estimated a mean CO_2 equivalent of 0.62 kg m^{-2} per year. Bustami et al. [8] were the only ones who included another empirical study by Charoenkit & Yimewattana 2017 [44] that found only a neglectable effect of green walls during a hot summer in a Mediterranean climate, resulting in inconclusive evidence. Vegetation species and substrates seem to have different capacities for carbon dioxide mitigation, so the overall mitigation effect might differ depending on GW's setup [17,40]. External effect modifications are mainly hypothesized through different climate zones [8] and daytime since the plant activity varies throughout the day [18]. Secondly, Ozone (O_3) mitigation was mentioned in one review [32] as a result of one modeling study by Jayasooriya et al. 2017 [45]. The authors report up to 298 kg of Ozone removal per year as a result of a simulation with 2 m high hedges around 88 building footprints. Thirdly, stormwater runoff mitigation potential was researched by Radic et al. and reported to be reducible by 4%, although these findings included green roofs [29]. Altogether the reviews above on the disaster risk reduction potential of green walls represent only eight unique studies, resulting in a low body of positive evidence.

3.2. Pathway restoration

Connections to restoration pathways were made in ten out of 30 reviews, including environmental comfort and wellbeing addressed in nine reviews, stress considered in five reviews and one review linked vertical greenery to a potentially positive effect on the human immune system (Table 6). Three reviews found positive effects of green walls on acoustic comfort [16,26,36]. They identified positive auditory effects of GW, as studied in listening tests where people's self-reported acoustic comfort was improved regardless of the dB levels. Green walls are also reported to be able to introduce natural sounds such as birdsong which are associated with a positive restorative effect [26,29]. Additionally, the presence of green walls and other biophilic infrastructures increases the presence of nature in the surroundings, which might improve the psychological well-being of citizens [13,21]. Furthermore, GW seem to increase the esthetic comfort of an area, making survey respondents repeatedly feel more connected with nature and report reduced stress levels [20]. In line with those findings, Goel et al. [21] reported lower stress levels of participants in GW scenarios compared to bare wall scenarios from visual and virtual experiments. Studies on thermal comfort were reported to be rare and should be a focus of further research, moving UHI studies from pure temperature reduction to thermal comfort [29,34]. The perception of air quality was not considered in any of the reviews. Regarding the potential effects of GW in strengthening the immune system, Pacini et al. [28] argue that the suggestions of Kuo 2015 [46] about the potential of the microbial diversity of greenery might also apply to vertical greenery. In summary, there seems to be only a limited body of evidence on the restoration pathway yet.

3.3. Pathway instoration

None of the included reviews reported studies reflecting on the potential instoration pathway between GW and health. Two papers made theoretical links about potential positive mechanisms between green

Table 5
Evidence on disaster risk mitigation.

Nr	Author	Year	Review method	Number of studies on the topic (empirical/total)	Studies categorized by	Disaster Risk Reduction	Extreme Rainfall	Climate Change	
								kg CO_2 eq / m^{-2} per year mean (min, max)	kg O_3 per year mean (min, max)
[29]	Radic et al.	2019	SR	1/5	climate zone	+ **	−4% stormwater runoff	- (-,-)	- (-,-)
[8]	Bustami et al.	2018	SR	1/2	country	0 *	- (-, -)	- (0.0, −0.62)	- (-, -)
[17]	Besir & Cuce	2018	NR	0/1	country	+ *	- (-, -)	−0.62 (−0.14, −1.00)	- (-, -)
[18]	Charoenkit & Yiemwattana	2016	SR (n/a)	0/1	climate zone and country	+ *	- (-, -)	−0.62 (−0.14, −1.00)	- (-, -)
[21]	Goel et al.	2022	SR (n/a)	0/1	city and country	+ *	- (-, -)	−0.62 (−0.14, −1.00)	- (-, -)
[28]	Pacini et al.	2022	NR	0/1	–	+ *	- (-, -)	−0.62 (−0.14, −1.00)	- (-, -)
[32]	Tomson et al.	2021	SR	0/1	city	+ *	- (-, -)	- (-,-)	-(-, −298.0)[a)]
[26]	Ode Sang et al.	2022	SR (n/a)	n/a	–	>	- (-, -)	- (-, -)	- (-, -)

Notes: Review method: NR = Narrative review; SR = systematic review; SR (n/a) = Systematic review without guidelines / Evidence Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes.

[a)] simulation with 2 m high hedges based on 88 plots, total area unknown [45].

Table 6
Evidence on restoration pathway.

Nr	Author	Year	Review method	Number of studies on the topic (empirical/ total)	Studies categorized by	Restoration Pathway		
						Envi. Comfort & Wellbeing	Stress	Immune System
[29]	Radic et al.	2019	SR	EC 4/7, S 1/1	climate zone	+ **	+ *	–
[20]	Ghazalli et al.	2019	SR (n/a)	EC+S 3/3	continent	+ *	+ *	–
[26]	Ode Sang et al.	2022	SR (n/a)	EC 1/1	–	+ *	>	–
[36]	Yang & Jeon	2020	SR	EC 3/3	–	+ *	>	–
[21]	Goel et al.	2022	SR (n/a)	S 2/2	city and country	–	+ *	–
[28]	Pacini et al.	2022	NR	S 1/1	–	>	+ *	>
[13]	Al-Kayiem et al.	2020	NR	n/a	–	>	–	–
[16]	Balderrama et al..	2022	SR	n/a	country	>	–	–
[34]	Wong et al.	2021	SR (n/a)	n/a	city	>	–	–

Notes: Review method: NR = Narrative review; SR = systematic review; SR (n/a) = Systematic review without guidelines / Evidence Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes.

walls and socializing activities (Table 7). These hypothesized effects are reducing violent behavior, increasing perceived safety [29], and increasing social interaction [21]. Ghazali et al. drew a connection between the environmental comfort that green walls might provide and a potential increase in outdoor activity [20]. No review linked the potential effect on dietary habits through edible plants situated in green walls.

3.4. Health outcomes

None of the 30 included reviews reported studies that directly measure health outcomes, although several links to known effects between nature and health outcomes are being made. Five reviews linked available evidence from horizontal green space to vertical green space (Table 8). All of them underlined the plausible connection to the improvement in restorative quality of a local environment that might benefit mental health. Three reviews theorize that the available strong evidence on heat mitigation shows a strong link to the potential reduction of cardiovascular diseases [20,26,28]. Other plausible effects are hypothesized as reducing respiratory-related illnesses through air pollution mitigation, and the potential for higher birth weight [26]. In summary green walls, just like green spaces, might reduce overall mortality and improve general health [20,26,36]. Although none of the reviews explicitly researched health outcomes and mostly used them as a rationale for their research, all theorize that existing evidence on horizontal green spaces might be transferable to GW as vertical green spaces.

3.5. Interrelated pathways

Through this holistic umbrella review some interdependencies between the mechanistic pathways become visible. For example, there might be a negative feedback effect between heat mitigation and air pollution since the cooling of vegetation slows down air circulation and can reduce the activity of plants [26]. Vegetated facades can increase biodiversity by attracting beetles, and spiders, especially for living wall systems, which might be helpful to strengthen the human immune system [6], but at the same time might also decrease environmental comfort and increase the amount of pollen [8,9]. Thus, GW might also serve as a habitat for disease vectors (ticks, mosquitos), which could increase the number of infections. Furthermore, the theorized restorative quality through the added environmental comfort can be considered an incentive to spend more time outdoors, reflecting its potential instoration effect. Lastly, the equally young research field on soundscape is linking multisensory approaches to better understand the effects of auditory, visual, thermal, and olfactory influences on perceived acoustic comfort [36]. There are likely more interdependencies to be discovered as pathways operate simultaneously. Multidimensional studies are needed to examine these interrelated mediating effects.

4. Discussion

4.1. Key findings

In our umbrella review, we systematically reviewed 30 reviews on the potential direct and indirect effects of green walls on health. These reviews included individual quantitative studies on 21 outcomes and additional qualitative references. Examined outcomes ranged from a reduction of particulate matter up to stress reduction alongside the three pathways of mitigation, restoration, and instoration. We found a strong consistent body of evidence that GW can reduce the surface temperature of bare walls by 0–31 °C, thus potentially mitigating the urban heat island effect, although the evidence on reduction of air temperature in urban settings is limited. We observed weak but consistent evidence that GW can reduce PM2.5 by 20–99%, PM10 by 23–60%, NO_2 by 15–64%, and SO_2 by a net removal rate (s^{-1}) from 1.05×10^{-6} to 1.11×10^{-6}. Additionally, we identified strong evidence that GW are able to mitigate noise in urban scenarios by 1–5 dB. Furthermore, we found some

Table 7
Evidence on instoration pathway.

Nr	Author	Year	Review method	Number of studies on the topic (empirical/total)	Studies categorized by	Instoration Pathway		
						Physical Activity	Socializing Activity	Diet
[20]	Ghazalli et al.	2019	SR (n/a)	n/a	continent	>	–	–
[21]	Goel et al.	2022	SR (n/a)	n/a	city and country	–	>	–
[29]	Radic et al.	2019	SR	n/a	climate zone	–	>	–

Notes: Review method: NR = Narrative review; SR = systematic review; SR (n/a) = Systematic review without guidelines / Evidence Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes.

Table 8
Evidence on health outcomes.

Nr	Author	Year	Review method	Number of studies on the topic (empirical/total)	Studies categorized by	Health Outcomes: General health	Mental Health	Mortality	Cardiovascular-related	Obesity-related	Respiratory-related	Cancer	Diabetes	Birth outcomes
[26]	Ode Sang et al.	2022	SR (n/a)	n/a	–	>	>	>	>	–	>	–	–	>
[20]	Ghazalli et al.	2019	SR (n/a)	n/a	continent	>	>	–	>	–	–	–	–	–
[28]	Pacini et al.	2022	NR	n/a	–	–	>	–	>	–	–	–	–	–
[36]	Yang & Jeon	2020	SR	n/a	–	>	>	–	–	–	–	–	–	–
[21]	Goel et al.	2022	SR (n/a)	n/a	city and country	–	>	–	–	–	–	–	–	–

Notes: Review method: N = Narrative review; S = systematic review; S (n/a) = Systematic review without guidelines / Evidence Direction: + = positive effect; - = negative effect; 0 = mixed evidence / Evidence strength: *** = strong evidence (90% of studies report consistent effect, at least 10 study results reported, at least 5 of those are empirical); ** = medium evidence (70% of studies report consistent effect, at least 5 study results reported); * = low evidence (70% of studies report consistent effect, 1–4 study results reported); (*) = low evidence but no explicit data on GW; > = theorized link to other pathways or health outcomes.

evidence that GW might be able to reduce stormwater runoff as well as mitigate carbon dioxide and ozone. Lastly, we identified a low but consistent body of evidence on the positive restorative effects of GW, namely higher environmental comfort, improved well-being, and reduced stress. We could not find a review or underlying studies explicitly researching the instoration pathway, neither on socializing behavior nor on physical activity. We also found no review and no underlying epidemiological studies focusing on the direct health outcomes of GW. But we did find similar mechanisms to green space health pathways, leading to likely true positive effects of GW on health.

4.2. *Potential mechanisms*

4.2.1. *Mitigation mechanisms*

We observed several similar mitigating mechanisms of green walls compared to those reported on green spaces. Both are built mainly on the effects of vegetation and soil/substrate to mitigate environmental stressors. But GW and green spaces seem to differ in effect size, which might be attributable to the two-dimensional nature of green walls, compared to green spaces.

To mitigate the Urban Heat Island effect GW can only rely on evaporation and the albedo effect. Shading, which is an important factor for green spaces, exists in green walls as a protective effect on the facade surface, but not in public spaces. At present, it is not yet clear which temperature reduction can be achieved at what distance from GW, but with clear tendencies towards a decreasing effect the greater the distance. This knowledge gap exists in large part because only smaller singular elements or individual facades have been used for the studies to date. To cool urban space, a larger-scale implementation of GW, over several facades constituting a public space, could potentially lead to significant effects.

GW mechanisms to mitigate air pollution showed strong similarities to green space mechanisms. Both essentially rely on the deposition and filtering capacity of leaves and soils. Differences are visible through spatial composition as a critical criterion for air exchange [47]. While the air exchange potential of connected green infrastructure is higher, it is shown that in street canyons the air exchange can even be hindered by trees [11]. For these narrow spaces, in particular, GW may therefore be the more effective option. Thus, we align with the frequent conclusion that more research is warranted to understand the air pollution reduction potential of GW [11,32].

GWs are likely capable of mitigating noise because of their porous structures as is also the case in sound-absorbing facade materials. There is evidence that noise mitigation through porous structures is performing best at mid to high frequencies (e.g. above 500 Hz) [27,48]. GWs designed considering absorption of low frequencies (e.g. road and air traffic noise) could potentially perform better than acoustic facade materials that lack the depth, layering, and differences in material densities offered by GWs. The design of the GW system, choice of vegetation species, and in the case of living walls, the substrate layer, determine the efficiency of sound-absorbing effects and sound-reflecting (e.g. scattering) effects. As a result, LW are more likely to perform better in noise mitigation than GF. Similarities between green walls and green spaces exist in sound perception by introducing natural sounds into the soundscape (see 3.2 Restoration). Differences are apparent due to the volume of green spaces compared to the two-dimensional wall surface. Green spaces achieve a large part of their reduction effects because of the distance that is established from the noise source. We observed that most of the studies on GW in the field of acoustics have been simulation studies or developed under controlled conditions such as reverberation chambers or laboratories through impedance tubes in order to determine the absorption coefficient. Thus, the acoustic performance of GWs implemented at a larger scale and tested under real-use conditions remains an underexplored field of research.

The effects of GW on disaster risk mitigation, similarly to green spaces, are connected to vegetation and the soil/substrate layer. While green space was able to reduce stormwater runoff by up to 27% in the study of Ferrini et al. [49], GW could only reduce stormwater runoff by 4% in the one reported empirical study and even included green roofs [29]. These differences can be plausibly related to the vertical nature of GW, limiting the space to capture rainfall by interception, stemflow, or throughfall into a substrate layer as the identified mechanisms [49]. Therefore, GW probably rely heavily on the volume of the substrate layer of LW to be able to delay water runoff significantly. More research is needed to quantify the potential of GW in general and LW in particular. Additionally, and despite the importance to reduce carbon dioxide in the atmosphere, the number of underlying studies that tried to quantify the potential of GW to mitigate carbon dioxide was very low.

Lastly, we acknowledge that the composition of species in green wall systems and its dimension is likely able to modify the relationships mentioned above. Furthermore, species composition likely modifies the measurable positive effect on biodiversity, which in turn is related to human health [50], and is one of the key points that classify interventions as Nature-based Solutions [51].

4.2.2. Restoration mechanisms

The restoration effects of GW are mainly based on the environmental comfort created by nature and through visual and auditory contact with nature itself. In this respect, GW and green spaces have quite similar mechanisms but again differ mainly in the volume of green spaces and the microclimatic comfort due to shading. Regarding the restorative effects of green spaces, reference is often made to the Attention Restoration Theory of Kaplan & Kaplan [52] and the Stress Reduction Theory of Ulrich [53]. While there was no study testing the attention restoration of GW, some initial studies found a consistent trend toward the stress reduction potential of GW. But the body of research regarding GW and restoration effects is still very thin and requires further studies.

4.2.3. Instoration mechanisms

GW are likely to increase the inviting nature of open spaces for physical activity and social interaction, as they seem to increase environmental comfort. Therefore, the mechanistic pathway between GW and instoration effects is similar to green spaces but with the difference in its only two-dimensional contribution to an existing urban space. Thus, GW effects seem to largely depend on other contextual factors of the urban setting in which they are a part, on the rest of the urban setting, whereas green spaces are able to create an inviting environment for physical activity or social interaction on their own. Therefore, the effect size might generally be smaller, but at the same time, new possibilities arise to increase the inviting nature of the existing urban fabric that is mostly composed of gray spaces and may be too dense for other green elements like trees. In addition, there is hypothetically the possibility to influence eating behavior by edible plants in LW. However, research on dietary behavioral changes is still in its infancy, even for green spaces. The instoration effects of GW were not investigated in any of the included reviews. This could be due to the few implementations of GW in real urban settings which leads to very few possibilities for research on human behavior. In general, these potential effects of GW to encourage health-promoting behavior are currently underexplored.

4.2.4. Health outcomes

Direct health outcomes were not studied in the reviewed literature. Again, this is likely caused by the rare implementation of GW in urban settings, especially at a larger scale, which makes epidemiological studies unfeasible. Despite these limitations, we did observe strong evidence on the mitigating pathway and to a lesser extent on the restoration pathway between GW and health. This already opens up a variety of effects on health outcomes, correctly linked by some of the included reviews [20,26,28,36]. Just as in green spaces in general, heat mitigation of GW might be able to reduce the prevalence of cardiovascular diseases. Air pollution mitigation of GW might lead to reduced respiratory-related illnesses and the risk of low birth weights. According to an estimation of UN—HABITAT, an estimated seven million people die prematurely each year as a result of air pollution alone [54]. In addition, there is evidence that air pollution and noise pollution are associated with anxiety, depression, and mental health in general [55–57]. Furthermore, as part of the building envelope, GW might have even more mitigating potential for indoor settings. Since the very function of a building envelope is to mitigate external emissions. Lastly, if the hypothesized instoration pathway of more physical activity, social interaction, and maybe even changes in dietary behavior hold, additional positive effects on the global disease burden of NCDs are to be expected. Thus, it is likely that GW are able to reduce overall mortality and improve general health, as well as overall well-being, even if not all mechanistic pathways have true effect sizes. Research on direct health outcomes of GW is highly warranted to confirm this theorized pathways.

4.3. Strength and limitations

Our umbrella review addressed all three positively associated pathways between green space and health to its applicability on green walls. We systematically examined reviews focusing on specific pathways and combined them to a holistic level of evidence on the potential health effects of green walls. Our review followed widely accepted guidelines like PICOS, PRISMA, and AMSTAR 2 to ensure a high-quality review. For data extraction, we used a semi-quantitative approach to extract available information from both narrative and systematic reviews in order to give an overview of the overall direction of associations. The review is fully transparent and comes with all related material.

We also acknowledge several limitations of our umbrella review. The quality of the underlying reviews largely determines the validity of our umbrella review. According to the quality check by the AMSTAR 2 protocol, almost all reviews are of very low quality (Table S4). It is important to note, however, that the high standards for reviews of the health sciences have not yet been widely adopted by many of the disciplines that produced the underlying reviews. Nevertheless, unsystematic and unpublished information are limiting factors for our umbrella review. In addition, the original studies often are of experimental nature or use simulations to come to conclusions. This further limits the validity of the findings for real-life complex urban settings. This is most likely due to the very young field of research and the very rare opportunities for in-field study designs, as there are still few large-scale implementations of GW in cities. Probably because of the same reason we could not identify an single study on direct health outcomes in the included reviews.

In addition, while we adopted a highly systematic approach to finding relevant literature, we only noticed during data extraction that we missed the term “environmental comfort” which is used by architectural disciplines. It refers to thermal comfort, acoustic comfort, aesthetical comfort, and air quality. Additionally we did not search specifically for carbon mitigation or stormwater management. In order to estimate the potential bias, we performed an additional search in SCOPUS with relevant keywords, leading to roughly the same reviews already included. Thus, we are confident that the potential bias caused by missed literature is relatively low. Nevertheless, we want to acknowledge, that while this umbrella review covered the main theorized positive pathways between green space and health, it does not comprehensively address every possible effect, especially since we did not focus on negative aspects like ecological disservices/causing harm domain or the high costs of installation and maintenance that are associated with living walls especially. Due to the wide science area, our umbrella review should not be seen as a comprehensive list of potential effects, but rather as an overarching summary of the current state of research on the main positive effect pathways of GW on health.

Further limiting factors were the heterogenous indicators and study designs used to measure the mitigating effects of green walls. We observed differing units for almost all kinds of mitigation potential. The particular matter was measured in reduction percentage or pure weight.

The underlying green wall size was not always reported, as well as the original pollutant level. The duration of the experiment was not always reported in the reviews, and when it was, it differed from one study to another. For ambient air temperature and noise mitigation, the point of measurement was often unclear and again differed from one study to another. For these reasons, most reviews refused to perform a meta-analysis.

Despite these limitations, we observed similar mitigating mechanisms, although in different sizes, between green walls and health compared to green space and health. This homogenous trend makes a true effect likely. However, more empirical, interventional, and long-term studies are needed to better understand the effects of GW on Health and the differences between these types of greenery.

4.4. Research gaps & future perspectives

The engineering origins of the research on green walls and energy savings are noticeable, but the area is starting to develop into a multidisciplinary field including a variety of topics viewed from different angles, such as public health. Regarding the direct and indirect health effects of GW, more evidence is needed based on rigorous study designs to verify the mechanistic pathways and better understand potential true effect sizes. We suggest adopting and adapting more of the green space health research methodologies to the domain of green walls and health.

The mitigation potential of GW has been researched the most in comparison to the other pathways but is still suffering from a limited number of in-field and longitudinal studies. For the urban heat island reduction potential of green walls, a better understanding of surrounding temperature reduction is warranted [27], especially in the real-life urban settings of different climate zones. In addition, the body of research is dominated by prototypes and laboratory settings [27]. More in-field UHI study designs are warranted. Modeling studies equally dominate study designs on air pollution mitigation and more empirical studies are requested [32,38]. According to Ysebart et al., the mitigation potential over a lifetime under different meteorological conditions remains also unclear, demanding longitudinal studies [38]. Similarly, the studies on the relationship between green walls on noise mitigation are dominated by controlled experiments, lacking real-use conditions with multiple sound sources [27]. Thus, more empirical, interventional, and longitudinal studies are warranted. In addition, it is theorized that effects on noise mitigation vary by substrate saturation or substrate composition of LW, but without evidence yet. The potential of green walls to mitigate carbon has rarely been quantified in the underlying studies of our included reviews. The same is true for the potential of living walls to mitigate the flooding risk of extreme weather events. While this might be to a small extent due to missed literature (see 4.6 strength & limitations), there seems to be nevertheless a low body of studies in this particular field. In summary, the few implemented GW in urban settings should be used extensively as research settings to better understand the mitigation potential of GWs under different circumstances.

Restoration effects of GW have rarely been researched up to this point. Especially the simultaneous impact of different aspects of environmental comfort needs more attention. For example, the non-auditory effects of green walls are often not recognized in studies about acoustic comfort [9]. However, Van Rentergehm et al. theorize three mechanisms to explain the positive impact on perceived soundscape via sound source invisibility, restorative potentials of vegetation, and vegetation-induced natural sounds [58]. In addition, since Medl et al. concluded in 2017 that the effects of green walls on stress recovery are a research gap, not much research on that topic has been conducted [25]. Although the effect of green walls on stress reduction is highly likely since there is evidence that the view of nature alone has a positive effect [59,60]. Coherently, Ghazali et al. recognize in 2019 that no studies have measured the psychological and physiological impacts of green walls [20]. Lastly, the effects of green walls on thermal comfort have rarely been studied. Wong et al. suggest moving forward from study design purely focusing on temperature measurement to thermal comfort [34]. We suggest increasing the number of studies in real urban settings, especially through multidimensional surveys, that can help to understand the simultaneous impact of different aspects of environmental comfort and their effect on stress and attention restoration.

Instoration effects of GW on more healthy behavior have rarely been researched up to now, although a true effect is likely and connected to a higher environmental comfort that might encourage people into spending more time outdoors [21], referring to the theories of Christopher Alexander, Jan Gehl, and Jane Jacobs [61–63]. Although these theories refer in large parts to active, transparent ground floor facades, leading to the question about the optimal ratio of green walls in an urban setting. More research in this area is warranted to understand the potential instoration effects of green walls, depending on the total urban setting in which they are a part. More observational studies, like behavioral mapping, could make potential differences in behavior visible.

Direct health outcomes deriving from GW have not been researched according to the reviews that we examined. Due to the limited number of implemented green walls, especially on a larger scale, it is not surprising that we could not identify a single epidemiological study. With the anticipated green transformation of our cities to tackle a variety of societal challenges, we recommend designing interventional studies alongside these transformations, to start closing this research gap. Recommendations on how to develop an impact evaluation together with all relevant stakeholders can be found in the Impact Evaluation Handbook [64,65] which is a combined effort of NBS innovation actions funded by the European Commission [66].

In general, it remains unknown which GW dimensions are needed to obtain any of the above theorized health effects. Additionally, some climate zones or geographic locations have not been studied up to date. Currently, there is an uneven distribution of research on the relationship between GW and health across climate zones [29,30]. The Cfa, Csb, Cwa, Cfa, Cfb and Af climate zones have received the most attention, with a focus on regions in Western Europe, Mediterranean countries, United States, East and Southeast Asia, and Australia. It is important to note that many other climate zones, especially those in the global south, have not been extensively studied in this regard and require further research. Furthermore, this field of research should elaborate on common study design, protocols, and reporting guidelines to better pool evidence and allow for meta-analysis. Lastly, multidimensional studies are warranted to explore the likely interlinkages between effect pathways.

5. Conclusion

NBS for our cities are associated with the potential to mitigate climate change and increase public health. We compiled and synthesized the potential positive effects of GW on public health, as a promising NBS for dense urban areas. We demonstrated consistent positive associations, although the body of evidence is still limited. It also became apparent that the young research field has not yet been able to conduct many studies in real urban settings, leading to a body of evidence of more experimental or theoretical nature. But since the observed mechanisms are similar to those of green spaces, where the body of evidence is stronger, we conclude that a range of positive true effects is likely. To verify this further research on direct and indirect health outcomes is needed. This makes it important to implement GW on a larger scale in pioneering projects as a necessary prerequisite for epidemiological studies. We recommend using these rare GW installations for cross-sectional studies, impact evaluations, and long-term follow-ups wherever possible to advance the young research field and provide the necessary evidence to decision makers to justify upscaling these urban nature-based solution.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is accessible in supplementary material.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nbsj.2023.100070.

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