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REVIEW
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# Planning, Designing, and Managing Green Roofs and Green Walls for Public Health – An Ecosystem Services Approach

Åsa Ode Sang[1]*, Petra Thorpert[1] and Ann-Mari Fransson[2]

[1] Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences, Alnarp, Sweden, [2] Department of Forestry and Wood Technology, Linnaéus University, Växjö, Sweden

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***Correspondence:**
Åsa Ode Sang
asa.sang@slu.se

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Installing green roofs and green walls in urban areas is suggested to supply multiple ecosystem services of benefit to human health and well-being. In a three-step literature review, we examined current knowledge on the link between public health and green roofs and green walls. A systematic search identified 69 scientific articles on green roofs/walls with a public health discourse. These articles were categorized according to type of health path covered (reduction of temperature, air pollution, noise or environmental appraisal) and coverage of issues of relevance for strategies on planning, design/construction, and maintenance of green roofs and green walls. Articles identified through the structured search were complemented with reviews (with no explicit public health rationale) covering reduction of noise, temperature, or air pollution and environmental appraisal. Other relevant studies were identified through snowballing. Several of the articles provided guidelines for optimizing the effect of green roofs/walls in supporting ecosystem services and maximizing well-being benefits to support health pathways identified. These included specifications about planning issues, with recommended spatial allocation (locations where people live, sun-exposed for maximum ambient temperature reduction) and with physical access needed for environmental appraisal. Recommendations regarding design parameters covered substrate depth (deeper generally being better), plant choices (more diverse roofs providing more services), and maintenance issues (moist substrate positively correlated with heat reduction).

**Keywords: temperature regulation, air pollution regulation, noise regulation, environmental appraisal, public health and well-being, green infrastructure, nature-based solution, living walls**

## INTRODUCTION

Green roofs and green walls have been promoted as features to improve the amount of urban green space, mainly within the dense city, motivated by their contribution to improving the urban environment (Norton et al., 2015). Lately, urban vegetation has received increased attention through the European Union's launch of nature-based solutions (NbS), where different forms of green infrastructure (such as green walls and green roofs) are seen as a measure for dealing with environmental and social issues within urban environments (e.g., Raymond et al., 2017).

Green roofs are a constructed system comprising vegetation growing on horizontal panels that are incorporated into existing built infrastructure and generally intended for environmental benefits, such as stormwater mitigation (Bengtsson, 2010). A green wall is part of what is called vertical greening or green facades (Köhler, 2008), defined as a building envelope based on living plants, and the term refers to all forms of vegetated vertical surfaces (Manso and Castro-Gomes, 2015). Green walls divided into green facades and living walls (Radić et al., 2019). In this review, we mainly focused on the living walls type, which can also be referred to as modular green walls (Köhler, 2008). Many previous review studies have identified a link between public health/well-being and natural environments, with e.g., a review by van den Bosch and Ode Sang (2017) summarizing the evidence on public health benefits from NbS. Most published studies assess health and well-being using a socio-ecological approach, where both environmental and social determinants are seen as contributing to health and well-being.

Section "Regulating ecosystem services – reduction of heat, pollution, and noise" summarizes the current understanding of actual health pathways for NbS, based on the framework presented by van den Bosch and Ode Sang (2017; see also **Figure 1**).

## Regulating Ecosystem Services – Reduction of Heat, Pollution, and Noise

Increased *urban heat* has been shown to be a strong predictor of a range of diseases [e.g., mental health, cardiovascular disease (CVD)] and all-cause mortality (Berry et al., 2010; Basagaña et al., 2011; Benmarhnia et al., 2015). Recent reviews have also indicated an association between heat load and decreased birth weight, although the evidence is inconsistent (Beltran et al., 2013; Poursafa et al., 2015). Urban heat affects mortality and morbidity through a combination of exposure to greater heat and vulnerability to extreme heat events, with heat sensitivity varying within populations and globally (Campbell et al., 2018). Another important factor influencing the effect of urban heat is behavioral exposure, i.e., the number of people using public open space (Norton et al., 2015).

Urban green space is reported to have potential in mitigating the urban heat island (UHI) effect, although the degree of mitigation is dependent on spatial location, vegetation type, and urban morphology (e.g., Bowler et al., 2010b; Norton et al., 2015). For instance, the mitigating effect of vegetation on UHI has been shown to be greater in densely built-up areas than in more sparse developments, with variations due to prevailing wind direction and time of day (Žuvela-Aloise et al., 2016). There is also seasonality in the effect of urban vegetation, with stronger effects in summer than early spring (Zhou et al., 2014). In addition to these broad differences in cooling, there is also variation linked to the level of soil sealing and amount of vegetation, which could explain micro-climate effects (Lehmann et al., 2014).

*Air pollution* adversely affects human health, resulting in an increase in respiratory illnesses such as asthma, a higher incidence of CVD (cardiovascular diseases), and impaired neural development and cognitive capacities (e.g., PopeIII, Burnett et al., 2002; Fann et al., 2012; EEA, 2016; WHO, 2016). The European Union has introduced legislation to improve human health by restricting different pollutants (e.g., $SO_2$, $SO_x$, $NO_2$, $NO_x$, $NH_3$, PM, CO, $O_3$, heavy metals, BaP, PAH and VOCs) (EEA, 2016). The main source of air pollution within cities is motorized traffic, but waste incineration, heating (domestic and thermal power generation), agriculture, and industry can have strong local effects (EEA, 2016).

Vegetation has the potential to mitigate air pollution. The density, height, thickness, and coverage of the vegetation, as determined by relative tree cover, tree size, and density, are the main characteristics determining the effect (Escobedo and Nowak, 2009; Tiwary et al., 2009; Tsiros et al., 2009; Dzierżanowski et al., 2011; Tallis et al., 2011; Nowak et al., 2013; Baldauf, 2017). However, there are differences between species (Benjamin et al., 1996). Uptake of gaseous and particulate pollutants is related to the morphology and physiology of plants (e.g., Beckett et al., 2000; Klingberg et al., 2017). For instance, traits such as compactness, plant hair density, plant leaf density, leaf wax, leaf surface area have been shown to influence particulate matter mitigation (Dzierżanowski et al., 2011; Hwang et al., 2011; Sæbø et al., 2012; Speak et al., 2012).

A WHO report published in 2011 concluded that noise has a negative impact on human health and that there is sufficient evidence of a relationship specifically with annoyance, sleep disturbance, CVD, cognitive impairment, and tinnitus (WHO, 2011). Noise exposure depends on the space-time behavior of individuals and differs between the residential, commuting, and work environment, with all three contributing to overall exposure and subsequent health implications (Díaz and Pedrero, 2006). Several studies have highlighted the positive influence of noise reduction through quiet urban areas, such as green spaces, and their possibility to act as a mitigating measure (Öhrström, 1997; Öhrström et al., 2006), while the vegetation itself also provides mitigation (Ow and Ghosh, 2017). Noise exposure in the urban context is largely due to motorized transport, but also construction and industry, community sources, and social and leisure sources, with the contribution of these sources varying spatially and over time (Moszynski, 2011).

Natural vegetation can reduce noise and contribute to a better soundscape (Viollon et al., 2002). Studies on traffic noise have shown that if the natural vegetation is sufficiently high, wide, and dense, it can decrease recorded noise levels (e.g., Viollon et al., 2002; Fang and Ling, 2003; Ow and Ghosh, 2017). For instance, it has been suggested that 30 m width vegetation can reduce noise levels by up to 8 dB (Huddart, 1990) or that 3 m width of dense vegetation can result in an attenuation of 5 dB (Kragh, 1981).

## Cultural Ecosystem Services – Socio-Behavioral Pathways

A range of health benefits are closely associated with socio-behavioral pathways and supply of cultural ecosystem services, requiring individual interaction with the environment. Studies on specific natural elements have provided knowledge about visual qualities and their impact on people's emotions and preferences associated with *environmental appraisal*. Recent reviews provide

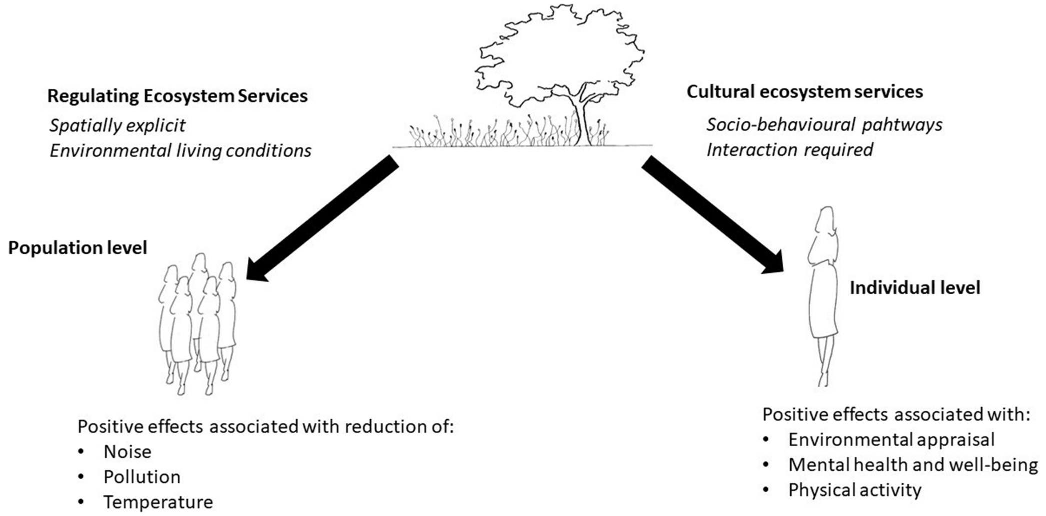


**FIGURE 1 |** Positive health benefits from urban green spaces, which are mainly associated with regulating and cultural ecosystem services. Regulating ecosystem services are spatially explicit and work on population level through improving environmental living conditions, while cultural ecosystem services are dependent on socio-behavioral pathways requiring interactions on individual level.

strong evidence of a positive impact of natural environments on behavioral affects and reduced levels of anger and sadness (Bowler et al., 2010a). Positive behavioral affect is in turn strongly related to CVD and all-cause mortality (Shirom et al., 2010; Lamers et al., 2012; Mroczek et al., 2013).

Visual properties such as openness (Hanyu, 2000; Jorgensen et al., 2002; Motoyama and Hanyu, 2014) and coherence (Motoyama and Hanyu, 2014) in a natural setting may have the potential to generate affective appraisals such as safety (Hanyu, 2000; Jorgensen et al., 2002; Motoyama and Hanyu, 2014) and relaxing and pleasant (Hanyu, 2000; Motoyama and Hanyu, 2014). Experience of naturalness has also been found to act as a mediator to experience of well-being (Knez et al., 2018). Ground cover features such as lawns are positively correlated with "rest and restitution" (Peschardt, 2014). A study by Nordh and Østby (2013) found that a "lot of grass and flowers/plants" were liked qualities, whereas absence of vegetation and presence of hard surfaces (pavement and buildings) decreased the perceived restorative qualities. Perceived visual quality has been found to increase with a high percentage of vegetation and presence of color contrasts (Arriaza et al., 2004), with a positive correlation also between visual preferences and medium to high plant species diversity and plant color composition (e.g., complementary color) (Polat and Akay, 2015). Recent reviews of the link between natural environments and health indicate that there is strong evidence of a positive relationship between natural environments and *mental health and well-being* (e.g., van den Berg et al., 2015). Several studies have reported restorative qualities of urban green space for coping with mental health problems (Barton and Pretty, 2010) and as a pre-emptive measurement for decreasing stress and providing "instorative" effects (e.g., Barton and Pretty, 2010; Nordh et al., 2011). In environmental psychology, restorative environments refer to environments that can trigger a psychological and/or physiological recovery process (Joye and van den Berg, 2013). Studies have shown that exposure to nature has restorative effects (Hartig, 2007), with healthy, unstressed participants reporting improvements in their subjective energy levels (Ryan et al., 2010), mood states, and ability to reflect (Mayer et al., 2009). While most studies to date have focused on the visual qualities of natural environments as a stress pre-emptive measurement, recent studies have highlighted the importance of natural sounds (such as birdsong) (e.g., Alvarsson et al., 2010; Annerstedt et al., 2013).

## Aim and Objective

The studies cited above were based on green spaces more generally, with few exploring specific types of green elements. Within the dense urban fabric, retrofitting of green roofs and green walls is often the only way of increasing the amount of green.

Our aim in this study was to explore whether, and to what extent, research findings on relationships between green spaces generally and public health apply to constructed green infrastructure such as green walls and green roofs. Our starting hypothesis was that when adequately planned, designed, and maintained, green roofs and green walls have the potential to supply the same human health and well-being benefits as green space in general. Therefore, we specifically examined evidence-based guidelines on green roofs and green walls issued within urban governance structures concerned with planning, design, and management issues.

# METHOD

In order to understand the discourses on public health benefits of green roofs and green walls, we conducted a three-stage literature review that combined a main systematic literature search with an additional systematic literature search (to identify additional relevant reviews) and a non-systematic literature search (snowballing technique; Almenar et al., 2021).

The systematic literature search was conducted in August 2021, using Scopus. We limited the search to peer-reviewed articles in English and used the following search term: (“**green roof***” OR “**green wall***”) AND (**health** OR **wellbeing** OR **well-being** OR **aesthetic).** After careful consideration, we decided not to include the term ‘barrier’, which is often used in relation to green walls in street-level settings, due to the multiple meanings of the term in relation to green space (e.g., physical barrier hindering access). Thus the search is likely to have missed some articles focusing on street-level features.

Since the aim of the review was to compile evidence of health and well-being benefits from green roofs and green walls, during screening of titles and abstracts for the initial search hits, we excluded articles with no connection to health-related performance and well-being. We categorized each remaining article according to type of study (review, empirical, simulation), the public health benefits discourse (noise, pollution, thermal, mental health/well-being, environmental appraisal), and aspect of green walls and green roofs (presence/location, design with regard to form, material, vegetation, performance as regards status and health of vegetation). In addition information on spatial context and measurements carried out was included when available.

Our second structured literature search was carried out in Scopus on 15 September 2021 and, in addition to the search terms Green wall* OR Green roof*, used the terms presented in **Table 1**. The aim of this second search was to identify reviews covering the health-supporting ecosystem services pathways identified by van den Bosch and Ode Sang (2017). **Table 1** shows number of published articles identified for each search string, the number of reviews within the total, and reviews relevant to our topic and hence included in our analysis.

The hits from the first systematic literature search were classified into the following three groups, based on type of study and where in the urban governance the results can be implemented:

(1) Planning: Location and placement of green roofs and green walls.
(2) Design: Design of components of green roofs and green walls.
(3) Management: Maintenance of green roofs and green walls.

# RESULTS

## Discourses on Green Roofs and Green Walls for a Health-Promoting City

The first systematic search in Scopus resulted in 207 articles, with 69 articles identified as relevant and included in our analysis (**Table 2**).

In the two structured literature searches we identified 20 reviews, of which several provided broad overviews of the benefits deriving from green roofs (Berardi et al., 2014; Francis and Jensen, 2017; Liu et al., 2021) and green walls (Medl et al., 2017; Ghazalli et al., 2019). For temperature and air quality regulation, there were numerous reviews dealing solely with these aspects, with 11 reviews focusing on temperature regulation (Bowler et al., 2010b; Hunter et al., 2014; Norton et al., 2015; Santamouris, 2015; Charoenkit and Yiemwattana, 2016; Santamouris et al., 2016; Francis and Jensen, 2017; Pisello et al., 2018; Cascone et al., 2019; Jamei et al., 2021; Liu et al., 2021) and six reviews covering different aspects of pollution (Rowe, 2011; Li and Babcock, 2014; Francis and Jensen, 2017; Corada et al., 2020; Liu et al., 2021; Ysebaert et al., 2021). For noise, we identified one review (Yang and Jeon, 2020). In relation to environmental appraisal and mental health, we found two reviews covering aspects of this (Fernandez-Canero and Gonzalez-Redondo, 2010; Williams et al., 2019).

The first structured literature search, which included a specific public health discourse (**Table 2**), mainly identified papers focusing on temperature and air quality regulation (25 and 23 hits, respectively). The second literature search (which did not include search terms related to public health) identified 705 and 420 articles dealing with the regulating services temperature and air quality regulation, respectively. For noise and environmental appraisal/mental health, fewer studies were identified in both structured literature searches. For noise, we identified eight articles in the first search and 91 in the second search, while for environmental appraisal we identified 10 articles in the first search and 166 in the second search.

Analysis of the hits revealed a direct discourse on the contribution of green roofs and green walls to public health and well-being in terms of regulating services such as reduction in temperature, pollution, and noise, but also in terms of positive environmental appraisal (**Table 2**). Within papers identified in the first structured literature search, the potential for green roofs and green walls to contribute to improved public health was discussed in relation to different spatial scales and contexts (**Table 2**). Most of the 37 articles reviewed focused only on the presence and location of green roofs and green walls, either measuring their impact in comparison with conventional roofs or measuring/simulating their impact on the surroundings. A number of the papers explored different aspects of design, such as species composition or substrate structures of green roofs and green walls (28 articles). Only a limited number of papers explored the status (either vegetation or substrate) of green roofs and/or green walls (five articles) in relation to effectiveness in providing public health-promoting ecosystem services.

The studies represented different governance structures, spatial scales, temporal phases for work with green roofs and green walls in health-promoting cities:

(1) *Planning for green roofs and green walls*. This included studies examining the presence and spatial location of green roofs and green walls for provision of health and well-being benefits on a more general level. These studies often compared conventional roof/walls with green roofs/walls or measured/simulated their impact on the surroundings, but without comparison of different variables such as vegetation and substrate.

**TABLE 1 |** Results of the second structured literature in terms of number of articles identified for each search string, number of review papers within the total, and reviews considered relevant for our analysis.

| Search terms | Hits | Reviews (of which relevant reviews included) |
|---|---|---|
| Pollution OR pollutant | 420 | 56 (Francis and Jensen, 2017; Corada et al., 2020; Liu et al., 2021; Ysebaert et al., 2021) |
| Noise OR sound | 91 | 13 (Yang and Jeon, 2020) |
| Temperature | 705 | 45 (Hunter et al., 2014; Charoenkit and Yiemwattana, 2016; Francis and Jensen, 2017; Cascone et al., 2019; Jamei et al., 2021; Liu et al., 2021) |
| Aesthet* OR preferenc* OR emotion OR appraisal | 166 | 22 (Williams et al., 2019) |

(2) *Design of green roofs and green walls.* This group of studies discussed and compared different types of green roofs and green walls, with regard to species and substrate and how they contribute to pathways for health and well-being associated with urban nature.

(3) *Management and maintenance of green roofs and green walls.* These studies touched upon the influence of maintenance and management of green roofs and green walls and their effect on the health pathways associated with urban nature.

## Green Roofs and Green Walls as Part of a Health-Promoting City

### Planning of Green Roofs and Green Walls Within the City – Location and Placement

A large proportion of the articles identified through the first structured literature search mainly focused on comparing green roofs/walls with conventional, not distinguishing specific types or just using one type in the empirical measurement/simulation.

Concerning the possibility of green roofs and green walls to contribute to temperature regulation, some of the studies provided support for this, mainly based on different types of simulations (e.g., Smith and Roebber, 2011; Herath et al., 2018; Gao et al., 2019, 2020; Huang et al., 2019; Zhu et al., 2021), but also experimental studies (e.g., He et al., 2020). Reviews by Bowler et al. (2010b), Santamouris (2015, 2016), Francis and Jensen (2017), Medl et al. (2017), Ghazalli et al. (2019), Jamei et al. (2021), and Liu et al. (2021) concluded that green roofs and green walls have potential for heat reduction, with the highest potential for temperature reduction in a dry climate (e.g., Smith and Roebber, 2011; Peng and Jim, 2013; Gao et al., 2020). The studies in our dataset also provided consistent evidence that the effect on temperature is highest during peak Urban Heat Island (UHI) periods, both in relation to season and to time of day (Bowler et al., 2010b; Speak et al., 2013; Santamouris, 2015; Solcerova et al., 2017; Gao et al., 2019, 2020).

Location in relation to wind direction also had an impact, with simulations by Zhang et al. (2019) showing that green roofs in upwind zones have better temperature reduction capacity for overall UHI mitigation. The review by Jamei et al. (2021) noted that few studies have been carried out specifically at pedestrian level or considering the thermal comfort for people. The few studies carried out showed that green roofs on lower-rise buildings have an impact on pedestrian level (Alexandri and Jones, 2008; Peng and Jim, 2013; Scharf and Kraus, 2019) and that installing green roofs on taller buildings has limited or no effect on pedestrian-level thermal comfort (Santamouris, 2015; Detommaso et al., 2021). For green walls/facades, some studies showed that their impact on the near surrounding outdoor air temperature is limited (e.g., Katsoulas et al., 2016), mainly occurs during peak solar hours (Cameron et al., 2014; Tan et al., 2014) and is limited to the close proximity of the wall (e.g., Wong et al., 2010; Cameron et al., 2014). Several studies emphasized the role of green roofs and green walls as part of an overall green infrastructure strategy to deal with the UHI effect, rather than use of green roofs and green walls as the only mitigation technique (Norton et al., 2015; Jamei and Rajagopalan, 2017; Santamouris et al., 2017; Herath et al., 2018; Zhu et al., 2021). Although green roofs and green walls were seen as less effective for thermal regulation than other green elements such as pocket parks and street trees, some studies concluded that they may play an important role when retrofitted in the dense urban environment (where space is limited) and spatially allocated to areas hosting groups vulnerable to heat exposure (Norton et al., 2015; Sanchez and Reames, 2019).

A factor related to cooling of the surrounding environment is *air quality*. Cold air is heavier than warm air and cooling slows down air circulation, while low temperatures also reduce the activity of the plants and their absorbing and filtering effect on air pollution. Cooling by green elements affects the airflow in such a way that air pollutants are dispersed close to roads, improving air quality (Baik et al., 2012). Less light also reduces surface-initiated photochemical reactions such as formation of ozone (Rowe, 2011), which is highly damaging to human health. Ozone is formed when NOx is transformed and reductions in gaseous pollutants is another way to reduce the amounts at ground level. Green roofs and green walls were reported to remove some gaseous pollutants (e.g., NOx, SOx, $CO_2$) from the air, but their effectiveness in removing other gaseous pollutants was less clear (Li et al., 2010; Rowe, 2011; Speak et al., 2012; Francis and Jensen, 2017; Medl et al., 2017; Liu et al., 2021).

Particulate matter (PM) in the air causes respiratory damage and negatively affects human health. Green roofs and green walls are reported to be efficient in reducing PM concentrations in air (Rowe, 2011; Francis and Jensen, 2017; Medl et al., 2017; Ghazalli et al., 2019; Weerakkody et al., 2019; Pettit et al., 2021). In general, larger particles are filtered from the air more efficiently by vegetation than smaller particles (Weerakkody et al., 2019; Tomson et al., 2021). Srbinovska et al. (2021) found that living wall plants removed up to 99% of coarse particles (PM 2.5), but the removal rate was less than 1% for particles less than 0.5 $\mu$m in diameter. A comparison with a non-vegetated surface in that study showed that the contribution

**TABLE 2 |** Articles (*n* = 69) recovered through a search in Scopus using the terms "green roof" OR "green wall" AND health OR wellbeing OR well-being OR aesthetic and after a scan of the abstracts.

| Author | Type of study | Focus | Type | Context | Species used | Specific details |
|---|---|---|---|---|---|---|
| **General** | | | | | | |
| Berardi et al., 2014 | Review | | GR | | | |
| Ghazalli et al., 2019 | Review | | GW | | | |
| Medl et al., 2017 | Review | | GW | | | |
| **Temperature** | | | | | | Temperature measurement |
| Bowler et al., 2010b | Review | | GI incl. GR and GW | NA | NA | NA |
| Detommaso et al., 2021 | Simulation | Planning | GI incl. GR | Urban | Extensive – no species listed though height 30 cm, LAI 1.50. | Outdoor temperature and mean radiant temperature, predicted mean and physiological equivalent temperature |
| Gao et al., 2019 | Simulation | Planning | GR | Metropolitan region | Not specified | Surface temperature |
| Gao et al., 2020 | Simulation | Planning | GR | Metropolitan region | Not specified | Surface temperature |
| He et al., 2020 | Experiment | Planning, design | GR | Urban | Sedum | Surface temperature, heat flux and humidity ratio |
| Herath et al., 2018 | Simulation | Planning | GI incl. GR and GW | Urban | Grass | Air temperature at 1.5 m height |
| Huang et al., 2019 | Simulation | Planning | GR | Metropolitan area | Not specified | Air temperature at 2 m height |
| Jamei and Rajagopalan, 2017 | Simulation | Planning | GR | Urban | Not specified | Physiological equivalent temperature<br>Mean radiant temperature |
| Li et al., 2014 | Simulation | Planning, management | GR | Metropolitan area | Not specified | Surface and near-surface temperature, atmospheric moisture |
| Lin et al., 2017 | Experiment | Design | GR | Urban | 12 ornamental plants most commonly used for extensive green roofs in Taiwan | Surface temperature, solar radiation intensity, substrate water content |
| Norton et al., 2015 | Review + observation | Planning | GI incl. GR and GW | Urban | Not specified | Not specified |
| Peng and Jim, 2013 | Simulation<br>Experiment | Planning | GR | Peri-urban to urban | Grass<br>Dense trees | Physiological equivalent temperature (PET) 1.2 above roofs and 1.2 m above street level ground |
| Pisello et al., 2018 | Review | | GR | NA | NA | NA |
| Sanchez and Reames, 2019 | Simulations | Planning | GR | Metropolitan region | Not presented | Land surface temperature |
| Sangkakool and Techato, 2017 | | Design | GR | | | |
| Santamouris et al., 2016 | Review | | GR + mitigation tech. | N/A | N/A | N/A |
| Santamouris, 2015 | Review | | GR | N/A | N/A | N/A |
| Scharf and Kraus, 2019 | Simulation | Planning, design | GR | Urban | Extensive | Air temperature, PET |
| Smith and Roebber, 2011 | Simulation | Planning | GR | Urban | Not specified | Apparent temperature |
| Solcerova et al., 2017 | Field experiment | Planning, management | GR | Urban | Sedum | Air temperature (15 and 30 cm above) |
| Speak et al., 2013 | Field experiment | Planning, management | GR | Urban | Intensive-mixed species: Rubus fruticosa, Buddleja davidii, Plantago lanceolata, Juncus sp., Aster novi-belgii, Senecio jaobaea, Agrostis stolonifera, Festuca rubra | Air temperature (30 cm above) |

*(Continued)*

**TABLE 2 |** (Continued)

| Author | Type of study | Focus | Type | Context | Species used | Specific details |
|---|---|---|---|---|---|---|
| Tan et al., 2017 | Experiment | Design | GR | Urban | Cyathula prostrata | Surface temperature, substrate temperature |
| Zhu et al., 2021 | Simulation | Planning | GR and GW + cool | High residential | Hedera helix, Funcia sp. | Building air temperature, canopy air temperature |
| **Air pollution** | | | | | | Type of pollutants |
| Abhijith et al., 2017 | Review | Planning, design | GR, GW | Urban pollutant reduction efficiency | Trees, perennials | General |
| Alsup et al., 2013 | Simulation/ observation | Planning | GR | | | |
| Baik et al., 2012 | Simulation | Planning | GR | Street canyons | Model green roof vegetation | NOx |
| Baraldi et al., 2019 | Experiment | Design | GR | Lab study Plant physiology and morphology | Perennial green roof species | General |
| Currie and Bass, 2008 | Simulation | Planning, design | GR | | | |
| Gnecco et al., 2013 | Field experiment | Planning | GR | Campus park building | Grass herbaceous plants | PM, metals, |
| Joshi and Ghosh, 2014 | Simulation | Planning | GW | Road side | Climber, Vernonia elaeagnifolia | SO2 |
| Jung et al., 2016 | Experiment/ simulation | Planning | GR | Urban | Model green roof vegetation | BOD |
| Li et al., 2010 | Experiment, simulation | Planning | GR | Urban | Perennial green roof vegetation/Ixora chinensis | CO2 |
| Li and Babcock, 2014 | Review | | GR | Urban | Perennial roof vegetation | General |
| Morakinyo et al., 2016 | Simulation | Planning | GW | Road-side | Model green wall vegetation | PM 2.5 |
| Ottelé et al., 2011 | Simulation | Design | GR and GW | | | |
| Pandey et al., 2015 | Field Experiment | Design | GW | Urban Pollution tolerance | Climbers | SO2, NO2, ozone, PM10 |
| Paull et al., 2018 | Experiment | Design | GW | | | |
| Paull et al., 2021 | Experiment | Design | GW | Urban field | Perennial green wall plants | Ambient pollution |
| Paull et al., 2019 | Experiment | Design | GW | Laboratory | Native Australian perennials | PM, VOC, CO2 |
| Pettit et al., 2021 | Experiment | Design | GW | Road side reduction efficiency | Westringia fruticosa (coastal rosemary), Myoporum parvifolium (dwarf native myrtle), Strobilanthes anisophyllus (goldfussia) and Nandina domestica (heavenly bamboo) | NO2, O3, PM 2.5 |
| Rowe, 2011 | Review | | GR | Urban | | General |
| Srbinovska et al., 2021 | Field monitoring | Planning | GR | Open urban areas | Urban vegetation | PM |
| Speak et al., 2012 | Field experiment | Planning, design | GR | Urban city center | Creeping bentgrass (Agrostis stolonifera), red fescue (Festuca rubra), ribwort plantain (Plantago lanceolata) and sedum (Sedum album) | PM 10 |
| Tomson et al., 2021 | Experiment | Design | GR and GW | Lab experiment | Black she oak (Allocasuarina littoralis), monkey rope vine (Parsonsia straminea), fringed wattle (Acacia fimbriata dwarf), and grass tree (Xanthorrhoea johnsonii) | PM |

*(Continued)*

**TABLE 2 |** (Continued)

| Author | Type of study | Focus | Type | Context | Species used | Specific details |
|---|---|---|---|---|---|---|
| Vera et al., 2021 | Experiment | Design | GR and GW | Plant reduction efficiency | Sedum album, Lampranthus spectabillis, Sedum spurium P, Lavandula angustifolia, Erigeron karvinskianus, Aptenia cordifolia, and Sedum palmeri. | PM |
| Weerakkody et al., 2019 | Experiment | Design | GW | Road side reduction efficiency | Buxus sempervirens | PM |
| Yang et al., 2008 | Simulation | Planning | GR | | NA | |
| Ye et al., 2013 | Simulation | Design | GR | Plant upptake | Sedum lineare Thunb, Sedum sarmentosum Bunge, Portulaca oleracea L., | Metals |
| Zhang et al., 2015 | Field experiment | Planning, design | GR | Urban | Buddha nail (Sedum lineare Thunb) | Nutrients, OC, Metals |
| **Noise** | | | | | | Noise reduction, decibels |
| Connelly and Hodgson, 2013 | Experiment | Planning, design, management | GR | Lab and in-field | Sedum | Transmission loss dB/Frequency |
| Connelly and Hodgson, 2015 | Experiment | Planning, design | GR | Lab and in-field | Extensive vegetated | Diffuse absorption coefficient/frequency |
| Jang et al., 2015 | Simulation | Planning | GR and GW | | | |
| van Renterghem and Botteldooren, 2014 | Experiment | Management | GR | Unclear | Sedum | Noise attenuation dB |
| van Renterghem and Botteldooren, 2009 | Simulation | Planning | GR | Street level | Extensive and intensive | Sound pressure level (dBA) |
| van Renterghem et al., 2013 | Simulation | Planning | GR and GW | Street level | Not specified | Absorption coefficient/frequency |
| Veisten et al., 2012 | Simulation | Planning | GR and GW | Street level | | Sound pressure level |
| Yang et al., 2012 | Experimental/ simulation | Design | GR | Experiment | Not specified | Absorption coefficient/frequency |
| **Environmental appraisal – mental health** | | | | | | Well-being function (aesthetic or al) |
| Collins et al., 2017 | Experiment | Design | GW | Urban | Variety of plant species | |
| Fernandez-Canero and Gonzalez-Redondo, 2010 | Review | | GR | N/A | N/A | N/A |
| Fernandez-Cañero et al., 2013 | Experiment/E | Design | GR | Urban | Variety of plant species | Aesthetic |
| Jungels et al., 2013 | Experiment | Design | GR | Peri-urban to urban | Sedum, grasses, mix of perennial plant species | Aesthetic |
| Lee et al., 2014 | Experiment | Design | GR | Urban | Variety of low growing plant species | Aesthetic Psychological |
| Liberalesso et al., 2020 | Review | Design | GR, GW | Hostel buildings | Not specified | Aesthetic Psychological |
| Loder, 2014 | Interviews | Planning, design | GR | Metropolitan area (Chicago, Toronto) | Prairie-style Sedum, grass-like Meadow-like | Aesthetic Psychological |
| Mesimäki et al., 2019 | Experiment | Design | GR | Urban | Mosses Sedum | Aesthetic Psychological Multisensory experiences |
| Vanstockem et al., 2018 | Case study | Design | GR | Imagine context situation | Sedum Herbaceous species | Aesthetic |
| Washburn et al., 2016 | Field experiment | Planning | GR | Peri-urban (airport area buildings) | Stonecrop species Sedum, Phedimus, Hylotelephium | |
| Williams et al., 2019 | Review | Planning, design | GR | Metropolitan area | Variety of plant species | Aesthetic Psychological |

*Each article was classified with regard to type of study, focus (e.g., planning, design and/or management), and type (GR, green roof; GW, green wall).*

of the green area was on average 25% reduction for PM 2.5 and 37% for PM 10 (Srbinovska et al., 2021). Unfortunately, smaller particles are more damaging to human health than larger particles (WHO, 2016), reducing the benefits from plants in this regard.

However, removal of pollutants from the air may be damaging to the plant, and some studies argued that the plants which are most efficient in removal would not survive long in polluted environments due to accumulation of contaminants in plant tissues (e.g., Paull et al., 2019). However, a later study by the same authors found that many species of plants exposed to urban air can withstand the polluted environment and show no signs of reduced vitality compared with non-exposed plants (Paull et al., 2021).

Overall, the articles in our dataset indicated that green roofs and green walls have the potential to reduce pollutants with negative effects on human respiratory functions, particularly when these green elements are located in the proximity of pollution sources such as traffic (Medl et al., 2017). A study by Morakinyo et al. (2016) highlighted the role of different horizontal/vertical patterns and magnitudes of upwind and downwind flow on relative concentrations of pollutants. These factors are depending on wind conditions and green element type and dimensions. Green walls may be able to reduce air pollution at pedestrian height, as indicated in the study by Morakinyo et al. (2016), but the interaction between filtering capacity and aerodynamic effect still needs to be evaluated. The location of a living wall or green roof is probably most critical for their efficiency in removing pollutants, with proximity to the pollution source and the effect on local wind conditions being the most important factors (Medl et al., 2017).

Studies exploring the *noise reduction* effect of green roofs and green walls showed that they can potentially have a positive affect on absorption and decrease transmission of noise (Veisten et al., 2012; Yang et al., 2012; Connelly and Hodgson, 2013, 2015; van Renterghem et al., 2013; van Renterghem and Botteldooren, 2014; Medl et al., 2017). Green roofs were reported to be more effective in reducing noise in quiet courtyards (van Renterghem et al., 2013) and at traffic noise levels over 1 kHz (Jang et al., 2015), while vegetated façades were reported to be better for narrow city street canyons (van Renterghem et al., 2013) and for reducing low-frequency traffic noise (Jang et al., 2015). While this gives some guidelines at city scale, Yang et al. (2012) identified a need for site-specific analysis of configuration and position of the system in order to maximize the reduction of noise. While those studies highlighted the noise reduction potential of green roofs and green walls, these green elements can also contribute toward positive noise in the form of bird life (Washburn et al., 2016), which has been shown to have a positive effect on estimated well-being (Hedblom et al., 2017).

Visual and physical access is evidently a key location-related aspect affecting the possibility of green roofs and green walls to contribute to positive preferences and emotion and to psychological well-being, human experiences associated with *environmental appraisal*. Several studies in our dataset emphasized the positive effect that viewing green roofs can have on esthetic enjoyment and provision of restorative experiences (Williams et al., 2019), such as emotions, affect, and psychological well-being (e.g., Ghazalli et al., 2019; Wong et al., 2010; Lee et al., 2014; Loder, 2014). Installation of green roofs and green walls at the planning stage could also contribute to local esthetic improvement (Liberalesso et al., 2020), and in the long-term leads to intensification of cultural ecosystem services and increased level of identity and sense of place (Eliasson et al., 2018).

## Implementation of Green Roofs and Green Walls – Design Parameters Affecting Health Pathways

Analysis of the literature in our dataset showed that substrate and species composition are the main design parameters affecting health pathways. Substrate type, and particularly the depth of substrate, were shown in some cases to have a positive relationship on provision of regulating services such as *temperature* (Santamouris, 2015; Charoenkit and Yiemwattana, 2016; Jamei et al., 2021), *air quality* (Rowe, 2011), and *noise regulation* (Connelly and Hodgson, 2015). The depth and composition of the substrate are also key factors determining the number of species that can be grown and their potential to thrive in green roofs and green walls. Studies comparing the effect of different species showed a positive relationship between canopy density and leaf area index (LAI), and regulating effects such as *thermal reduction* (Kolokotsa et al., 2013; Cameron et al., 2014; Hunter et al., 2014; Lin et al., 2017) and *air quality improvement* (Rowe, 2011; Baldauf, 2017).

With regards to *temperature regulation*, in relation to substrate types the study by Tan et al. (2017) showed effects of substrate composition, with the highest temperature found when topsoil was used as substrate and demonstrated that incorporation of a water retention layer can have positive effects in retaining soil moisture and on evapotranspiration rate. Vegetation coverage ratio was reported to be an important factor in the ability of green roofs or green walls to contribute to temperature reduction (Fang, 2008; Berardi et al., 2014; Lin et al., 2017; Ghazalli et al., 2019; Zhang et al., 2019). However, vegetation traits such as LAI and leaf morphology were also shown to play an important role (e.g., Fang, 2008; Morau et al., 2012; Berardi et al., 2014; Jamei et al., 2021), increasing the shading effects of the vegetation. The studies in our dataset were limited in number of species included, and with few repetitions, something also highlighted as a limitation by Ysebaert et al. (2021). Species reported to have good cooling effects in green walls include *Salvia* (Monteiro et al., 2017; Jamei et al., 2021), *Hedera* and *Stachys* (Cameron et al., 2014). Different species were found to contribute to cooling in different ways, with *Fuchsia* spp. providing evapo-transpiration cooling, while *Jasminum* and *Lonicera* contributed shade cooling (Cameron et al., 2014). Other studies showed that the vegetation must be dense to provide cooling effects (Chang et al., 2007; Bowler et al., 2010b). According to Lin et al. (2017), locations with high intensity solar radiation and a more sophisticated design of green roof (with high plant coverage, plant height, albedo, and canopy volume) can be expected to contribute more toward cooling capacity, and hence the effect would be more beneficial.

In relation to *air quality*, the structure and layout of the vegetation is important and studies have shown that vegetation density, LAI, thickness, and height are important for air flow and speed, where particles are deposited when the air speed is reduced, and vegetation alters the flow of the air (Baldauf, 2017). Species traits has been shown to influence ability for air quality purification (Liu et al., 2021; Ysebaert et al., 2021). For instance, leaf morphology is an important factor in PM removal (Speak et al., 2012; Paull et al., 2019) and species with high photosynthetic capacity, stomatal conductance, and transpiration are efficient in removing all gaseous pollutants from the air (Baraldi et al., 2019). A review by Liu et al. (2021) concluded that air quality purification ability is higher for intensive green roofs than for more extensive green roofs. But also differences among species occur. Speak et al. (2013) showed that *Agrostis stolonifera* and *Festuca rubra* are more effective than *Plantago lanceolata* and *Sedum album* at PM 10 capture. However, plant vitality may be negatively affected by plant uptake of pollutants. Several studies (Paull et al., 2018, 2021) reported that the most common green wall plant species are able to withstand highly polluted environments. There were no conclusive results on species differences on the best capacity for survival and pollutant removal (Paull et al., 2021), although native Australian species seem to have lower capacity (Paull et al., 2019). In one study, edible plant species (*Sedum lineare*, *Sedum sarmentosum,* and *Portulaca oleracea*) grown on green roofs were found to accumulate heavy metals, especially cadmium (Cd), at levels rendering the plants inedible (Ye et al., 2013). The effect of pollutant remediation on the filtering plants needs further research.

The *noise absorption* effect of green roofs and green walls is reported to be dependent on substrate depth, organic matter content, plant establishment, and moisture content (Yang et al., 2012; Connelly and Hodgson, 2015). Noise absorption increases with substrate depth, percentage organic matter, and plant establishment (Connelly and Hodgson, 2015). However, the configuration of the system seems to be more important (Yang et al., 2012), although more systematic studies on different type of layouts are required. Another aspect of noise is its transmission, which decreases for roofs with vegetation, particularly in the case of low-frequency noise (Connelly and Hodgson, 2013).

Design parameters of green roofs and green walls, such as species composition, are linked in the literature to health pathways and associated *environmental appraisal*. An attitude study by Liberalesso et al. (2020) found that potential hostel users support integrated installation of green infrastructure and consider that green roofs and green walls could provide esthetic improvement and stimulate sense of well-being. Analysis of the literature indicated that building-integrated vegetation, such as ivy facades and meadow-inspired roof vegetation appear to be more aesthetically pleasing and have the ability to generate higher restorative qualities than e.g., sedum or turf roof vegetation (White and Gatersleben, 2011). However, Mesimäki et al. (2019) indicated that low-grown grassy vegetation surrounded by a dense urban area can also generate recreational benefits, while Jungels et al. (2013) found that grass-dominated green roofs generate negative esthetic reactions compared with sedum-dominated or mixed perennials, which were experienced as fresh, innovative, and beautiful. One explanation for this is their messiness (Jungels et al., 2013; Loder, 2014). Green roofs

| Planning | Design | Management - Maintenance |
|---|---|---|
| ***Regulatory ecosystem services - reduction of heat, pollution and noise***<br>• Spatial match problem (pollution, noise, UHI ) with vulnerable groups<br>• Positive effects are within short distance for pollution, noise and temperature (0.4 m) – placement should be where people are = at pedestrian level<br>• Placement should be in dry climate with high air quality and sunexposed for maximum ambient temperature reduction<br>• Green elements affect the air flow to spread near roads, which improves the air quality.<br>• Green roofs for high and low frequency traffic noise<br>• Green walls at street canyons and green roofs on courtyards for noise reduction.<br>***Cultural ecosystem services – socio-behavioural pathways***<br>• Visual/physical access needed for environmental appraisal | ***Regulatory ecosystem services - reduction of heat, pollution and noise***<br>• High organic matter increases noise absorption and air quality<br>• Structure and layout of the vegetation influence air quality<br>• Deeper substrate is positively correlated to heat, noise and pollution reduction, and support a more layered vegetation.<br>• More vegetation layers/LAI/vegetation depth is positively correlated to heat, noise and pollution reduction.<br>***Cultural ecosystem services – socio-behavioural pathways***<br>• Variety in vegetation structures (trees, shrubs, perennials, succulents) has a higher contribution to environmental appraisal and in turn emotion, affect and psychological well-being.<br>• Flowering species and variety of colours has a higher contribution to environmental appraisal and in turn emotion, affect and psychological well-being. | ***Regulatory ecosystem services - reduction of heat, pollution and noise***<br>• Well irrigated substrate is positively correlated to heat reduction, and provide more and healthier vegetation.<br>• Well irrigated substrate risks leaking pollutants.<br>• A healthy vegetation with a large leaf biomass will capture and take up pollutants more efficiently.<br>***Cultural ecosystem services – socio-behavioural pathways***<br>• Messiness of the vegetation affects the environmental appraisal and in turn emotion, affect and psychological well-being. |

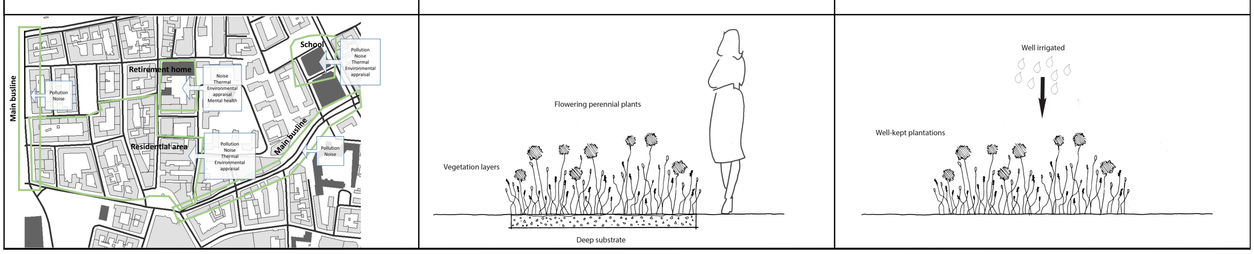


**FIGURE 2 |** Guidelines for optimizing the effect of green walls and green roofs in delivering public health-supporting ecosystem services.

that contain a variety of colors and vegetation structures are reportedly more likely to be preferred if well designed and regularly maintained (e.g., Fernandez-Cañero et al., 2013). Some studies indicated that flowering vegetation has higher restorative value than succulents (Lee et al., 2014), as well as being positively associated with creative thinking, health, well-being (Loder, 2014), and increased sustained attention (Lee et al., 2015). These findings stress the need for careful design of green roofs and green walls to supply environmental appraisal, especially since research has shown variations in their provision of psychological benefits (Williams et al., 2019) and fulfill people's desires (Mesimäki et al., 2017).

### Maintenance and Management of Green Roofs and Green Walls to Maximize Public Health Benefits

Concerning the effects of maintenance and management on the performance of green roofs and green walls and the relationship to public health effects, very few studies in our dataset looked specifically at those aspects. Similarly, few studies looked at positive health-contributing factors over the longer term with regard to roof life-span, despite a call for such studies (e.g., Buffam et al., 2016).

In efforts to ensure that green roofs and green walls fulfill their potential to provide public health benefits, a key aspect is irrigation, which affects both substrate and vegetation health. Well-saturated substrate has greater *cooling capacity* (Li et al., 2014; Santamouris, 2015; Solcerova et al., 2017; Jamei et al., 2021) compared with dry substrate. In relation to *pollutant*, the study by Todorov et al. (2018) showed that a well-irrigated system may leach pollutants to a higher extent, and hence systems for handling this negative effect need to be put in place. For *noise reduction*, the effect of substrate water content is suggested to be limited (e.g., van Renterghem and Botteldooren, 2014).

Irrigation also affects the health of vegetation, manifested by a higher LAI density and hence better effect when it comes to the reduction of *temperature*, *pollution*, and *noise* (Speak et al., 2013; Hunter et al., 2014). Several studies on the effect of green roofs and green walls on *environmental appraisal* concluded that maintenance is an important aspect for preferences (e.g., Fernandez-Cañero et al., 2013; Jungels et al., 2013; Loder, 2014), with the presence of scruffy and dried vegetation considered negative.

## CONCLUSION AND FUTURE RESEARCH

Our analysis of the relevant literature showed that green roofs and green walls can supply regulating ecosystem services and cultural ecosystem services, supporting pathways for public health. This effect could be maximized by adequate planning, design, and management of the resources (**Figure 2**).

Analysis of the literature provided strong evidence for regulating ecosystem services (heat reduction, improved air quality and noise reduction) and cultural ecosystem services (improved affect) from green roofs and living walls. *Heat reduction* through vegetation has shown to have a strong link to reduction of CVD (cardiovascular diseases) mortality, as well as all-cause mortality and mental disorders. The reviewed literature provided good evidence of the potential contribution of green roofs and green walls within an overall green infrastructure strategy in mitigating UHI, and thereby potentially reducing CVD mortality, all-cause mortality, and mental disorders in urban areas. This potential appeared to be greatest for urban centers, which are predicted to be significantly affected by increases in temperature due to future climate change. Due to the positive effects occurring only within a short distance from the installation, adequate planning should be carried out before investments in green roofs and green walls is done, and urban morphology and locations of vulnerable human groups to achieve the best health effects in relation to UHI should be taken into account. Through appropriate design of these systems, with plants with a high LAI in well-irrigated and deep substrate, the positive effects could be increased compared with more extensive and thin types of green roofs. However, providing moist systems with optimal plants is a challenge in areas suffering from water shortages, and for which the benefits would be greater.

*Air pollution* affects human health mainly through an increase in respiratory illnesses such as asthma, a higher incidence of CVD, and impaired neural development and cognitive capacities. Green roofs and green walls have the potential to mitigate air pollution, through reduction of gaseous pollutants such as NOx, SOx, and $CO_2$, but also PM (with higher particles more effectively filtered), and with the largest effect received close to the air pollution source. When designing green roofs and green walls, the effectiveness of these could be improved through design and layout of the system taking the pollutant source and dominant wind conditions into account. This includes also the type of substrate as well as vegetation types used. For instance, using a heterogeneous topography of the vegetation layer and species with high LAI, photosynthetic capacity, stomatal conductance and transpiration, the filtering and uptake of gaseous pollutants could be improved. Providing a system that is moist provides healthier plants that in turn has better air filtering potential.

There is evidence that *noise* has a relationship with public health aspects such as annoyance, sleep disturbance, CVD and cognitive impairment. Studies have shown that green roofs and green walls could absorb and decrease transmission of noise, though some suggestions are that green roofs works best in already fairly quiet court yards and green walls being better for narrow street canyons. Both have the potential of adding positive sound through the potential habitat for birds. The depth of substrate as well as percentage organic matter is positively influencing the ability of green roofs to deliver noise regulating, while level of water content is less clear. With regards to the vegetation, plant cover, but also canopy density and leaf area index are also important to maximize in order to gain maximum noise regulating effects.

For *environmental appraisal*, the study by van den Bosch and Ode Sang (2017) showed strong evidence of a reduction in all-cause mortality and CVD mortality, but weak evidence of a reduction in mental disorders. In our review, only a limited number of studies focused on environmental appraisal from green roofs and no studies were identified for green walls. The available evidence indicates that, to achieve the environmental appraisal effect from green roofs and green walls, they need to be visually accessible at a minimum. The status and character of the vegetation also appear to be important in maximizing this effect. This means providing a sufficiently deep substrate level to support healthy, well-irrigated vegetation with a variety of vegetation structures and colors. However, these studies included in this review in relation to environmental appraisal have mostly been carried out in Europe, North America and Australia, so the global validity is unclear. Recent studies on global validity of landscape preference has questioned this to be the case (e.g., Hägerhäll et al., 2018).

Our review of the literature focused on positive health impacts, but green roofs and green walls could also have negative effects in some cases, such as emissions of nutrients and heavy metals through stormwater run-off or contamination of edible species, posing potential health risks. Other disservices identified for green infrastructure in general included exposure to allergenic pollen, presence of animals as disease vectors, and discomfort from the presence of animals or their droppings, although research on these in relation to green roofs and green walls was sparse.

Compared with similar vegetation on the ground, green roofs and green walls are more costly in terms of installation and maintenance, which limits their cost-effectiveness as a city-wide NbS strategy. However, in a dense city setting they can provide a space efficient NbS for areas where other types of urban vegetation are not feasible and can provide public health benefits for residents in those areas. In general, the ecosystem services from green roofs and green walls appear to be most efficient in providing public health benefits when located close to where people live or work. Placing these structures close to where people spend time, i.e., on low buildings and structures close to the ground, will have the greatest effect on human health. In the case of noise and particle pollution sources such as roads, a location close to the source would be most efficient.

When analyzing the positive contribution that green roofs and green walls could make to public health and well-being, we focused on the public health pathways provided by regulating and cultural ecosystem services. However, our analysis showed that, in order to achieve these positive effects, well-functioning green roofs and green walls are needed. For example, a thin substrate layer with insufficient level of irrigation loses its cooling ability and noise reduction capacity, as well as limiting the variation in vegetation structure (and in turn in flowering species and variety of colors), providing a lower level of environmental appraisal compared with non-vegetated roofs.

While the literature includes empirical studies covering most aspects relating to public health pathways, there is a lack of studies on the long-term effect of ecosystem services supplied by green roofs/walls. For instance, the long-term effects of green roofs and green walls in sustained reduction of noise, temperature, pollution, and esthetic values are not well studied. There is also a lack of research on how to maximize ecosystem services that support public health and well-being through adequate and cost-effective maintenance of green roofs and green walls across the seasons.

## AUTHOR CONTRIBUTIONS

ÅOS initiated the manuscript, carried out the structured searches, and was the main responsible for the writing of the manuscript. PT contributed to the development of the analytical framework, was main responsible for the section on environmental appraisal as well as the illustrations, and contributed to the development of the conclusions and future research. A-MF was main responsible for the sections on reduction of air pollution and contributed to the conclusion and future research. All authors contributed to the article and approved the submitted version.

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