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REVIEW

Green Walls as Mitigation of Urban Air Pollution: A Review of Their Effectiveness

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ABSTRACT

Mitigation of urban air pollution has been constrained by the availability of urban spaces for greening. Green walls offer the prospect of greening spaces and surfaces without requiring large areas. Green walls can largely be divided into green facades where the aboveground parts of plants rooted in soil and pots grow directly on, and living walls holding bags, planter tiles, trays and vessels containing substrates in which plants are grown. Green facades and living walls can be continuous or modular with repeating units that can be assembled for extension. This review aims to present the effectiveness of green walls in removing different types of air pollutants in indoor and outdoor environments. It examined more than 45 peer-reviewed recently published scholarly articles to achieve the aim. It highlights that most of the studies on green walls focus on particulate matter removal and green walls could effectively remove particulate matter though the effectiveness varies with plant types, air humidity, rainfall and its intensity, leaf area index and contact angle, green wall surface coverage ratio, as well as the height of green walls. Increasing the height of green walls and optimizing their distance from roadsides could promote the deposition of particulate matter. Washing off could regenerate plant surfaces for capturing pollutants. Green walls are also effective in removing NO_2, O_3, SO_2 and CO. Indoor active living walls, when properly designed, could have air purifying performance comparable to a HVAC system. The performance of green walls could be optimized through polycultures, selection of plants, surface coverage and height, and air inflow.

Keywords: Air pollution; Green facade; Leaf surface; Living walls; Particulate matter; Outdoor

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1. Introduction

Major urban centers around the world are frequently plagued by air pollution which not only poses a threat to the health of the urban inhabitants but brings economic implications due to affected health [1]. Urbanization causes increasing migration of people to cities, leading to intensified air pollution and greater health implications due to exposure to polluted air. As of 2019, approximately 99% of the world's population did not have access to air that met the World Health Organization's guideline limits, particularly those in developing countries [2]. Taking India for instance, the annual death associated with air pollution in 2019 hit 1.67 million, higher than any other nations globally and this was translated to an economic loss of $36.8 billion, equivalent to 1.36% of India's gross domestic product in 2019 [3]. Air pollution in India has been perceived as a major hindrance to its economic growth and public health improvement [3].

Particulate matter (PM) is a major contributor to air pollution. The fine fraction of PM capable of penetrating deep into the lungs increases the risks of respiratory diseases, lung cancer, heart disease and stroke [4]. Indoor air pollution caused by home stoves and open fires is a major concern, posing a risk to approximately 2.4 billion people worldwide [2]. In comparison to indoor air pollution, outdoor air pollution is often contributed by more diverse sources ranging from domestic emitters, transportation, agriculture and industry [5]. Both indoor and outdoor air pollutions lead to an estimated 7 million premature deaths yearly. In the past three decades, the severity of outdoor air pollution has risen significantly especially in developing countries with India seeing a 115.3% increase in death rate associated with the outdoor PM as opposed to a 64.2% decrease in death rate linked to indoor air pollution with poor ventilation [3]. Outdoor pollution caused by ozone has increased the air pollution-related death rate by 139.2% in India as outdoor air pollution intensifies in relation to industrial development, transportation and power generation [3].

Air pollution is related to climate change in the sense that certain air pollutants such as ground-level ozone, nitrous oxide, methane and hydrofluorocarbons are greenhouse gases [6]. Methane, for instance, is responsible for 1 million deaths annually and has a 100-year global warming potential of 27-30. Reducing air pollution offers the co-benefit of reducing global warming, particularly through the removal of air pollutants which are greenhouse gases [7]. Lockdowns during the COVID-19 pandemic led to improved air quality and reduced greenhouse gas emissions in multiple regions [8]. It offered hope of meeting the target of the Paris Agreement to cap global warming at 2 °C or a more stringent 1.5 °C if the trajectory of greenhouse gas reduction could be maintained [8]. However, the lifting of lockdown as nations progressed to adapt to COVID-19 has reversed the emission reduction attained [9]. Air quality deteriorates and air pollution returns to the level before COVID-19. Greenhouse gas emissions increase in tandem with mounting air pollution [10].

It becomes apparent that the benefits on air quality stemming from travel restrictions are short-lived and it is impractical to perpetuate such restrictions due to the humongous socioeconomic consequences [11-13]. Therefore, lasting measures to alleviate air pollution, especially in urban centers are crucial. These measures are multi-pronged and are aimed at polluting sectors comprising primarily energy, transportation and industry. They could be regulated through monitoring of emissions from these sectors and imposing control on the quality of emissions, as well as technology-oriented involving the use of cleaner production technologies and processes, and the replacement of fossil fuel-powered vehicles with electric vehicles [14]. In addition, best practices that reduce the release of air pollutants such as the development of public transport system, promoting energy-saving behaviors and sustainable consumption are beneficial [15]. There is also increasing interest in establishing green lungs to curb urban air pollution. However, it has been met with limited land for green spaces in urban areas. Since plants play essential roles in purifying air and breaking down some of the pollutants, the emergence of green walls and green roofs permits optimal greening of urban structures to facilitate urban air cleansing [16].

Currently, there are few review articles examining the effectiveness of green walls in mitigating indoor and outdoor air quality. The existing reviews revolve around the types and functions of green walls [17] as well as their general features and designs [17]. There are also reviews examining the specific functions of green walls particularly their ability to alleviate urban heat and energy use [18], and particulate pollution in cities [19]. Oquendo-Di Cosola et al. (2022) reviewed the ability of green walls in regulating buildings' temperature and attenuating noise [20]. Studies dedicated to the economic facet, as well as the costs and benefits of green walls are available [21,22]. There is an apparent gap in the review of whether green walls could effectively reduce indoor and outdoor pollution. This review, therefore, comprehensively presents the effectiveness of green walls in mitigating different pollutants in indoor and outdoor environments. It examines more than 45 peer-reviewed scholarly papers, published primarily in the past 10 years to identify if green walls were effective in removing various pollutants indoors and outdoors.

2. Green wall designs

Green walls stemmed from the constraints faced in greening spaces in urban centers which are often limited. The little room available in cities to set up sizeable green belts and spaces to buffer against air pollutants has sparked the search for alternatives to enable the greening of unconventional areas or structures, thus giving rise to greening systems particularly green roofs and green walls [19]. Green systems enable the establishment of plants to shield and reduce pollution while increasing the esthetic values of structures. They have the potential to improve the performance of buildings, hence their sustainability through reducing energy consumption and carbon emissions [23,24]. Green walls are essentially the establishment of plants on the walls of building structures. They could be traced back to ancient structures such as the Hanging Gardens of Babylon with plants grown on cascading manmade structures [16]. They were also evident in residential buildings in UK and Europe in the seventeenth and eighteenth centuries characterized by walls covered with climbers. Unlike those of the earlier era, the modern green walls are designed for specific functions while providing ornamental function. They are akin to the idea of green facades for enhancing ecological functions which became popular in the 1980s [25].

Establishing green walls typically involves vegetating vertical surfaces such as partitions, facades and walls and in some instances, they are named vertical greening systems or green vertical systems interchangeably [26,27]. Green facades were the earliest form of green walls with climbers or hanging plants grown on the facades. Green facades could be direct with plants growing on walls, and indirect where plants grow on support structures attached to walls (**Figure 1**). In either case, plants are grown in soil or pots and are allowed to extend or develop upward [27]. Indirect green facades may adopt continuous support extending throughout the entire surface where greening is intended or modular support consisting of components such as vessels and repeating support units that can be assembled (**Figure 1**) [17]. Green facades are constrained in terms of height and are not suitable for high-rising buildings. The plants suitable for green facades could be limited and it takes longer time for plants to establish thereon. The growth of plants on green facades may not be even [17]. However, depending on the types, green facades offer certain advantages. Direct green facades are uncomplicated and cost-effective though they potentially give rise to maintenance problems and deterioration of wall surfaces [27]. Continuous indirect facades have low water consumption. Modular indirect facades provide the ease of assembly and dismantling for maintenance and plants replacement, in addition to systematic irrigation. Indirect facades are generally more cost- and material-intensive than direct facades [16].

Living walls allow greening to be performed on the walls of high-rising buildings over larger wall areas in a shorter timeframe. They can be purpose-fitted to different types of buildings and have the benefit of growth uniformity on walls [17]. Like indirect green facades, living walls are categorized as continuous or modular, where the former involves the erection of lightweight and permeable frame on which plants are individually attached, and the latter comprises repetitive units with media for plants to grow (**Figure 1**). The units are assembled with a joining structure or onto the walls directly [28]. The common units are flexible bags, planter tiles, trays and vessels. Flexible bags can be used on walls of different designs and they typically consist of light and durable bags with growing media [28]. Planter tiles are incorporated into buildings' designs similar to tiles except that they could hold plants. Trays are essentially containers for plants and substrates that can be interconnected through an interlocking mechanism while vessels for living walls are tailored to enable fastening to vertical structure or to each other [17]. Trays and vessels often require support that they could be fastened to. Planter tiles, however, can be glued or attached onto walls like tiles [25]. Continuous living walls permit the uniform growth of plants and the establishment of diverse plant types. The system distributes water and nutrients uniformly to plants. They have the drawbacks of being complex, water- and nutrient-demanding as well as cost- and maintenance-intensive [28]. Modular living walls have the advantage of suiting different wall designs and surfaces due to the availability of different modules. However, the installation could be complex, often incurring high cost and requiring large amount of materials [21].

Modular green wall elements, be it indirect green facades or living walls require substrates for plant growth. The substrates can be organic, inorganic or a mixture of both [23]. Modular living walls for instance, often require a mixture of substrates with granular and porous characteristics such as a combination of granular particles and fibrous materials for good water retention. The addition of nutrients is crucial to promote plant growth and health. The substrates may be covered with geotextile bags or individual lids to hold them in place [16]. As for direct green facades, plants are grown in soil and do not require separate substrates [27]. Continuous living walls usually employ a hydroponic system to support plant growth [17].

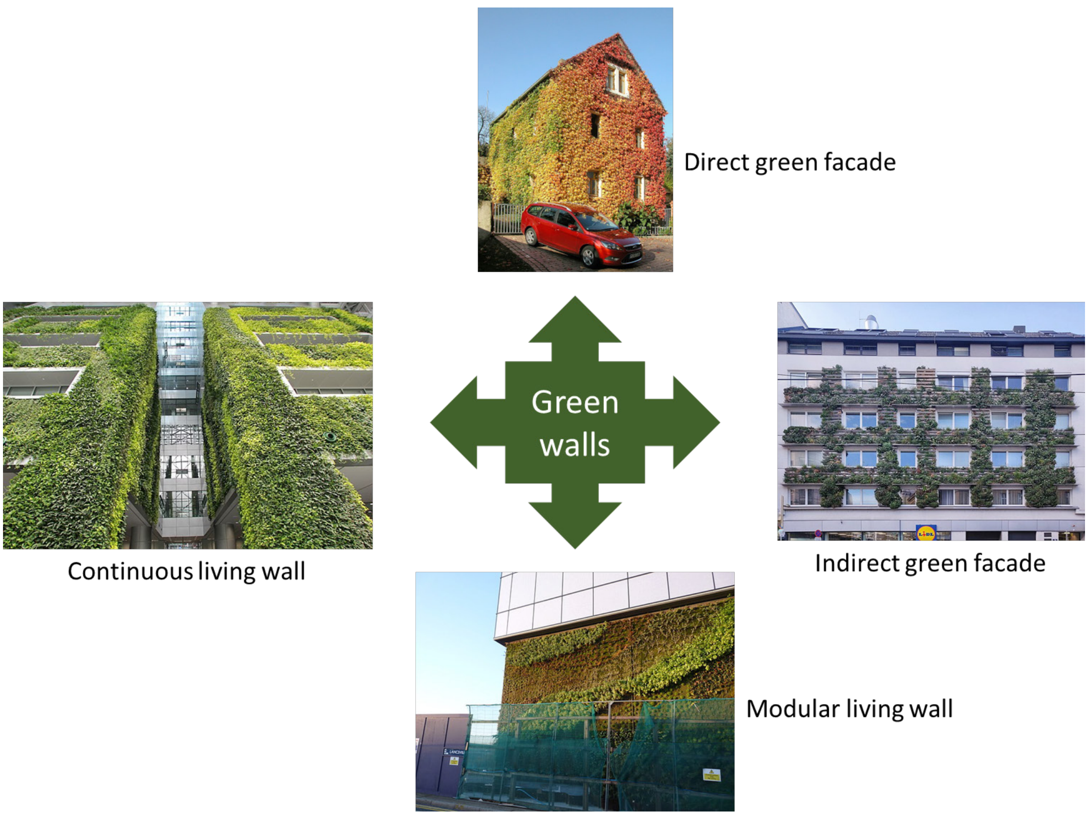

Figure 1. Different types of green walls.

The choice of vegetation for green walls is determined by building features and regional climate to ensure the successful establishment of plants [28]. Climbers are the most popular options for green facades as some climbers could stick to the wall without support. Some climbers such as vines, however, require support. They could face limitations in climbing heights with some species reaching greater heights than others. Climbers could take as long as five years to reach maximum heights [23]. It was found that Virginia creeper (*Parthenocissus quinquefolia*) established quickly under Mediterranean Continental climate while the growth of *Clematis* sp. was compromised in summer [27]. The flexibility of living walls to different esthetic ideas permits various plant species ranging from grasses, ferns, flowering plants and shrubs to be incorporated. An enabler of this is the hydroponic system employed which could support different types and forms of plants as long as there are adequate supplies of water and nutrients in the system [20]. While a wide range of plants could be the candidates for green walls, sustainability needs to be considered to realize the full potential of green walls as an environmentally friendly alternative for alleviation of air pollution. For instance, there has been interest in the use of succulents because they have low demand for water and low maintenance [17]. Green walls could also provide an avenue for growing crops, vegetables and herbs in land-deficient urban centers to boost food production [23].

3. Effects of green walls on air pollution

3.1 Outdoor environments

Recent studies on green walls center either on the effectiveness of such walls generally or specific types of green walls to remove air pollutants under different outdoor settings. The ability of the walls to remove PM has been extensively studied (**Table 1**). Green walls have been reported to effectively reduce PM of different sizes. A green wall of 7 different plant species was reported to be effective in removing $PM_{2.5}$. The removal efficiency was determined by the species of plants and their positions on the wall [29]. Green walls containing a variety of plant species were deemed more effective in removing $PM_{2.5}$ than those of a single plant species [29]. In a roadside setting, a green wall of *Hedera Helix* was reported to gather more PM, particularly that sized 10-100 μm, than those at a rural site attributed probably to vehicular movement which emitted PM and caused dust dispersion. *H. helix* gathered substantially more dust on dry roadside than wet roadside [30] (**Table 1**). An examination of the metal contents of the PM revealed variations with one reporting Fe, Zn, Pb, Mn and Cd to be most abundant in a descending sequence [31] while another finding Mg to be the most abundant (1558 mg kg^{-1} DW), followed by Mn and Ti [30]. The PM and metal particles seemed to gather on the leaves of *H. helix* more than the wax and the metal contents differed depending on the sources which are often diverse [30].

H. helix is a popular plant used in the study of green walls and is commonly planted on green facades. It is either planted alone or in combination with other plant species. For instance, a green screen and living wall containing *H. helix* and 3 other plant species were found to have different PM-gathering performances under different rainfall events [32]. High-intensity rainfall (41 mm hr^{-1}) resulted in more PM being washed off the plants than low-intensity rainfall (16 mm hr^{-1}). Under all rainfall circumstances, the PM gathered on the plants decreased and washing-off could be a potential way to regenerate PM capturing surfaces on green walls [32]. In a separate study, *H. helix* was compared with 3 other plant species on a vertical greening system in terms of PM-capturing ability and it was revealed to have an intermediate performance, capturing less PM than *Trachelospermum jasminoides* but more PM than *Cistus* 'Jessamy Beauty'. The study generally found more PM $\leq$ 2.5 was collected than PM $\geq$ 2.5 [33] (**Table 1**). Like the other studies, Fe was detected in the PM on the leaves. Besides, Si and Ca were detected, confirming the variability of metal contents of PM [30,31,33]. A study on another green wall of only *H. helix* unveiled temporal variation of PM capture over the winter months with more PM_{10} and $PM_{2.5}$ trapped in December than in March. PM capture was negatively correlated with leaf surface contact angle [34]. Besides PM, a green screen of *H. helix* was tested in its ability to remove NO_2 and was reported to reduce mean NO_2 concentrations by up to 23%, hence effective in mitigating daytime NO_2 [35].

A study by Viecco et al. (2021) examined the layout of green walls instead of the plant species employed in capturing $PM_{2.5}$ and found that buildings with 25% surface coverage ratio of green walls provided the optimal $PM_{2.5}$ capture. In the study, the heights of the buildings did not affect the optimal $PM_{2.5}$-capturing efficiency [36]. While most studies on the effectiveness of green walls in removing air pollutants are experimental, there are also studies that are simulation-based. Simulation-based studies typically examined the removal of a wide range of pollutants. A study using i-Tree Eco software to simulate the removal of NO_2, SO_2, PM_{10}, CO, $PM_{2.5}$ and O_3 by 2-m green walls of *Laurus nobilis* for commercial and industrial premises reported different amounts of the pollutants removed where the amount of O_3 removed (298 kg yr^{-1}) was the highest, followed by PM_{10} (214 kg yr^{-1}) and NO_2 (kg yr^{-1}) [37]. Simulation with a Reynolds-averaged Navier Stokes model and a revised generalized drift flux model unveiled PM_{10} removal to be positively correlated with leaf area densities and green coverage. Multiple factors comprising block morphology, plant density, green wall coverage and plant types affect PM_{10} capture [38]. This implies the variability of removal efficiencies even for the same air pollutant due to numerous factors at play.

A simulation conducted by Morakinyo et al. (2016) for a green wall unveiled the effectiveness of the wall in reducing $PM_{2.5}$ under different wind scenarios and that increasing the height of the wall rather than its thickness improved its PM-capturing ability [39] (**Table 1**). The study showed green walls promote the deposition of $PM_{2.5}$ and limit the dispersion of roadside pollutants, in line with the study of Przybysz et al. (2014) revealing more dust deposited on green walls established at roadside dry sites [30,39]. In addition, simulation of the ability of a green facade with *Vernonia elaeagnifolia* to filter SO_2 emitted by vehicles demonstrated different SO_2 deposition velocities with respect to open (1.53 mms^{-1}) and closed (0.72 mms^{-1}) stomatal pores of the plant [40]. SO_2 was removed at a higher rate under dry conditions (1.11×10^{-6} s^{-1}) than humid conditions (1.05×10^{-6} s^{-1}), echoing the findings that dry conditions favor the removal of air pollutants by green walls, probably because wet conditions and rain result in wash-off effect and dissolution of air pollutants with relatively high aqueous solubility [30,32,41]. Nonetheless, PM wash-off might differ among plant species and PM sizes. Perini et al. (2017) observed PM sized 2.5 to 10 μm was not easily washed off from *Phlomis fruticosa* and *H. helix* [33].

The use of active green walls has been garnering attention. Unlike conventional green walls which remove pollutants through passive diffusion of air through the walls, active green walls are equipped with mechanisms to actively draw air through the walls acting as biofilters. Pettit et al. (2020) tested the effectiveness of an active green wall containing 4 different plant species in removing NO_2, O_3 and $PM_{2.5}$ from ambient air polluted by wildfire emissions and reported a respective 63.2%, 38.8% and 24.8% reduction of the pollutants [42] (**Table 1**). Clean air delivery rates of the 5 m^2 active green wall were 558.9 m^3/h, 343.2 m^3/h and 219.8 m^3/h for NO_2, O_3 and $PM_{2.5}$ respectively [42]. Weerakkody et al. (2018) examined the PM-trapping capacity of 20 plant species on a 100 cm^2 living wall and revealed that the needles of *Juniperus chinensis* L. was most effective in trapping vehicular PM of all sizes [43] (**Table 1**). The wall, which did not have an active mechanism, was capable of trapping 122.1×10^7 PM_1, 8.2×10^7 $PM_{2.5}$ and 4.5×10^7 PM_{10}. Species with smaller leaves and conifers were found to have better effectiveness in removing PM generated by traffic [43]. This is probably also associated with leaf area index and leaf surface contact angles of the plants [34,40,44].

Table 1. Effectiveness of green walls in removing air pollutants in outdoor and indoor environments.

Green Wall Type	**Plant**	**Pollutant**	**Findings**	**Reference**
Outdoor Environments				
Green facade	Ivy (*Hedera helix*)	Metal particles	Abundances of metal PM deposited on the leaves were in the sequence of Fe, Zn, Pb, Mn and Cd.	[31]
Green wall generally	Polycultures comprising *Aptenia cordifolia*, *Erigeron karvinskianus*, *Lampranthus spectabillis*, *Lavandula angustifolia*, *Sedum album*, *Sedum spurium* P., *Sedum palmeri*	$PM_{2.5}$	Species of plants and their positions on green walls determined the effectiveness of $PM_{2.5}$ capture. Polycultures might have higher effectiveness than monocultures in removing $PM_{2.5}$ over the long term.	[29]
Green wall generally	*Hedera helix*	PM and trace elements	*H. helix* at roadside dry sites accumulated 8.0 to 140.6 μg/cm^2 of PM. *H. heli*x at rural sites gathered the lowest PM. *H. helix* at roadside dry sites accumulated up to 1420% more dust than that at sites exposed to rain over the study period. PM sized 10-100 μm was most collected. *H. helix* at roadside dry sites accumulated large amounts of Mg (1558 mg kg^{-1} DW), Mn (146 mg kg^{-1} DW), Ti (10.8 146 mg kg^{-1} DW). All metal particles, except Mo were slightly higher or higher on *H. helix* at roadside dry sites than roadside wet sites. PM and metal particles gathered on the leaves of *H. helix* more than the wax.	[30]
Green screen (a type of green facade) and living wall	*Heuchera villosa* Michx*, Helleborus x sternii* Turrill*, Bergenia cordifolia* (Haw.) Sternb.*, Hedera helix L.*	PM	Rainfall reduced the PM gathered on the plants. High-intensity rainfall (41 mm hr^{-1}) washed off more PM on the plants than low-intensity rainfall (16 mm hr^{-1}). Green walls are potential recyclable PM traps which can be regenerated through wash-off. 16 mm hr^{-1} rainfall caused greater PM_{10} wash-off from the plants.	[32]
Vertical greening system generally	*Trachelospermum jasminoides*, *Hedera helix*, *Cistus* 'Jessamy Beauty', *Phlomis fruticosa*	PM_{10} and $PM_{2.5}$	*T. jasminoides* collected the largest number of particles, followed by *H. helix* and *Cistus* J. B. The largest fraction of particles collected was those between 0.5-1 μm, followed by those between 1-1.5 μm. More PM ≤ 2.5 was collected than PM ≥ 2.5. Particles sized 2.5 to 10 μm were not washed off from *P. fruticosa* and *H. helix* leaves by rainwater. Fe, Si and Ca were the most abundant elements on the leaves of the experimental plants.	[33]
Green wall generally	*Hedera helix*	PM_{10} and $PM_{2.5}$	*H. helix* trapped 0.1613 mg cm^{-2} PM_{10} in December and 0.0383 mg cm^{-2} PM_{10} in March, indicating temporal variation in PM_{10} capture. Temporal variation of $PM_{2.5}$ was also observed with *H. Helix* capturing 0.1557 mg cm^{-2} $PM_{2.5}$ in December and less than 0.04 mg cm^{-2} $PM_{2.5}$ in March. Leaf surface contact angle is a determinant of PM capture capacity. The correlation is a negative one.	[34]

Table 1 continued

Green Wall Type	**Plant**	**Pollutant**	**Findings**	**Reference**
Green wall generally	Not available. The study focuses on the layout.	$PM_{2.5}$	$PM_{2.5}$ capture was the highest with 25% surface coverage ratio (excluding doors and windows) for green wall, in comparison to 50%, 75% and 100% coverage. Green wall is effective in capturing $PM_{2.5}$ for buildings with different heights (5 m, 10 m, 20 m and 30 m).	[36]
Green wall generally	Simulation using i-Tree Eco software. 2-m green walls of *Laurus nobilis* for industrial and commercial premises were simulated.	NO_2, SO_2, PM_{10}, CO, $PM_{2.5}$, O_3	NO_2 removal = 87 kg yr^{-1} SO_2 removal = 26 kg yr^{-1} PM_{10} removal = 214 kg yr^{-1} CO removal = 10 kg yr^{-1} $PM_{2.5}$ removal = 10 kg yr^{-1} O_3 removal = 298 kg yr^{-1}	[37]
Green wall generally	Simulation with a Reynolds-averaged Navier-Stokes (RANS) model and a revised generalized drift flux model.	PM_{10}	PM_{10} reduction ratios increase as leaf area densities and green coverage increase. PM_{10} capture is affected by factors such as block morphology, plant density, green wall coverage and vegetation types.	[38]
Green wall generally	Simulation with ENVI-met model.	$PM_{2.5}$	Reduction of $PM_{2.5}$ was observed after passing through green walls under different wind conditions. Increasing the height of green walls has greater beneficial effect on the air quality after the walls than increasing their thickness. Green walls promoted deposition of $PM_{2.5}$. Green walls help to limit the dispersion of pollutants from highways.	[39]
Active green wall acting as botanical biofilter	*Myoporum parvifolium*, *Westringia fruticosa*, *Stobilanthes anisophyllus*, *Nandina domestica*	NO_2, O_3, $PM_{2.5}$	NO_2, O_3 and $PM_{2.5}$ were reduced by 63.2%, 38.8%, 24.8% after the ambient air polluted by wildfire emissions was passed through the green wall without recirculation. For each 5 m^2 active green wall, the clean air delivery rates for NO_2, O_3 and $PM_{2.5}$ were 558.9 m^3/h, 343.2 m^3/h and 219.8 m^3/h respectively.	[42]
Green facade	Simulation with *Vernonia elaeagnifolia* as the air purifying plant	SO_2	Vehicular SO_2 deposited at open and closed stomatal pores at a velocity of 1.53 mms^{-1} and 0.72 mms^{-1} respectively. Under dry and humid conditions, SO_2 was removed at a rate of 1.11 x 10^{-6} s^{-1} and 1.05 x 10^{-6} s^{-1} respectively. SO_2 removal was also affected by leaf area index. *V. elaeagnifolia* attained a high leaf area index in a relatively short time and is a good candidate for SO_2 removal.	[40]
Green screen	*Hedera helix*	NO_2	Mean daily NO_2 concentrations reduced by 22%. Mean hourly NO_2 reduction of 23% was reported. The screen was effective in removing NO_2, particularly in the day.	[35]
Living wall generally	20 plant species	PM	A 100 cm^2 living wall was capable of trapping 122.1 x 10^7 PM_1, 8.2 x 10^7 $PM_{2.5}$ and 4.5 x 10^7 PM_{10}. The needles of *Juniperus chinensis* L. was observed to trap the most PM of all sizes. Species with smaller leaves and conifers were generally more effective in removing PM generated by traffic.	[43]

Table 1 continued

Green Wall Type	Plant	Pollutant	Findings	Reference
Indoor Environments				
Active green wall	*Epipremnum aureum, Nephrolepis exaltata, Peperomia obtusifolia, Schefflera arboricola, Spathiphyllum wallisii*	PM, total volatile organic compounds (TVOCs)	An active green wall resulted in approx. 73% lower TVOCs and PM than the control (active wall without plant) in an indoor environment. Active green wall could remove an additional 28% TVOCs (in 20 mins) and 42.6% PM as compared to an operating HVAC system. TVOCs were possibly removed through adsorption on substrate. PM were removed through deposition on plant and filtration by substrate.	[45]
Indoor active living wall biofilter	*Chlorophytum comosum*	PM_{10} and $PM_{2.5}$	A 0.25 m^2 biofilter reached a maximum total suspended particulate (TSP) filtration efficiency of 53.4% when the air flow rate was 11.25 Ls^{-1} (without air recirculation). The PM_{10} and $PM_{2.5}$ removal efficiencies were 53.4% and 48.2% respectively. The biofilter had lower TSP and PM removal efficiencies than an HVAC filter system capable of removing 85.8% TSP, 78.4% PM_{10} and 77.8% $PM_{2.5}$.	[46]

3.2 Indoor environments

Compared to outdoor environments, there are fewer studies on the effectiveness of green walls in removing indoor air pollutants and most of the studies have been conducted for active green walls or living walls. Pettit et al. (2019) experimented on the ability of an active green wall comprising 5 plant species to remove PM and TVOCs, and found the wall to result in approximately 73% lower PM and TVOCs than the control which was an active wall without plant [45]. The wall was more effective than an operating HVAC system in removing PM and TVOCs over a 20-min duration (**Table 1**), probably through filtration of PM and adsorption of TVOCs by the substrate used [45].

Another study by Irga et al. (2017) found that a 0.25 m^2 indoor active living wall of *Chlorophytum comosum* provided optimal filtration efficiency of 53.4% at an air flow rate of 11.25 Ls^{-1} without air recirculation. The removal efficiencies of PM_{10} and $PM_{2.5}$ reached 53.4% and 48.2% respectively [46] (**Table 1**). However, in comparison to an HVAC system, the active living wall had lower TSP and PM removal efficiencies [46]. This contrasts with the findings of Pettit et al. (2019) that their active green wall was more effective than the HVAC system in removing PM and TVOCs [45]. The reason could be due to the differences in the plant composition and the substrate used. The active green wall of Pettit et al. (2019) had a polyculture of plants which could also contribute to higher removal of PM since polycultures were deemed to be more effective than monocultures in the long-term removal of PM [29,45]. The applications of active living walls in indoor environments present an understudied area that could be further probed as indoor biofilters not only provide esthetic values but help with improving indoor air quality.

4. Conclusions and recommendations

Green walls are generally found to be effective in removing air pollutants in indoor and outdoor settings as well as controlling the dispersion of pollutants from roadsides, either through experimental or simulation-based studies. In outdoor environments, different types of green walls have been reported to reduce the abundance and promote the deposition of PM of different sizes, but PM deposition is compromised by rainfall wash-off. Wash-off provides an avenue for regeneration of PM trapping surfaces of green walls. PM removal by green walls is affected by factors comprising plant species, leaf surface contact angles, leaf area index, green wall coverage, buildings' morphology and plant density. Besides PM, green walls are also able to significantly remove NO_2, SO_2, CO and O_3. In indoor environments, active green walls could be effectively used to remove PM and TVOCs. This review highlights the prospective use of green walls in the removal of a wide array of pollutants. It systematically presents the effectiveness of green walls in ameliorating indoor and outdoor air pollution. It promulgates the use of active living green walls in indoor environments in light of their comparable effectiveness to a HVAC system and their esthetic value. To enhance their effectiveness, the following recommendations are made:

Plants with large leaf area index or could attain large leaf area index in a short time could be used for green walls [34,40].

Polycultures could be established instead of monocultures [29,45].

Green walls are made recyclable through washing off the PM trapped on leaf surfaces [32].

Surface coverage ratios of green walls could be optimized for optimal performance (e.g. 25% coverage ratio) [36].

The heights and distances of green walls from roadsides could be optimized for optimal performance [30,39].

Air inflow rate of active living walls could be optimized for optimal removal of pollutants [45,46].

Plants with high adaptability and are resilient to air pollutants such as ferns, ivy and pothos are good candidates for green walls [31,47].

Recyclable materials could be used for green walls to reduce the waste from maintenance and replacement of green walls bound for landfills.

Governments may roll out policy instruments to promote the installation of green walls.

Conflict of Interest

There is no conflict of interest.

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