Living walls in indoor environments

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ABSTRACT

The warming climate, projected increase in frequency and severity of extreme heat events, and the long-established heat island phenomenon are all expected to exacerbate urban environmental thermal loading. Active means used for addressing such risks are likely to increase energy consumption and emission trends to create a positive feedback loop that could threaten the health and wellbeing of urban citizens. In response, passive approaches such as green infrastructure enhancements are widely advocated, and to meet the challenges of implementing enhancements in dense cities, attention has been directed toward encouraging surface greening. This paper recognises this trend and considers vertical greening as a developing interest with application opportunity in both exterior and interior urban environments. A review of available studies and interviews with experts found most observations available to be derived from exterior applications. Interior applications consequently have yet to be investigated to determine relative value to indoor environments where most of human habitation is typically concentrated. The integration of plant science studies in this regard is highlighted as essential to develop a balanced evidence base for the enthusiasm observed for promoting indoor living wall installations.

Keywords: urban greening; vertical greening; living walls; indoor plants; indoor environment

1. Introduction

In response to the call for encouraging passive approaches such as green infrastructure enhancements to address climate risks, surface greening has received much attention particularly in cities with dense morphologies. Although initial efforts had targeted the promotion of horizontal greening measures to achieve enhancements, vertical greening has gained significant favour particularly since the turn of the century. The evidence of this is seen today in most cities where installations are increasingly introduced to new as well as existing building facades. The aesthetic appeal and interest that such flourishing exterior installations generate have in turn encouraged their integration into the more interior aspects of buildings, which over the past few years has resulted in a significant upward trend in commissions received by specialist installers [1]. Although many other vegetation-based ecosystem services are voiced by advocates, investigations of interior applications are scarce, which highlights the need for evidence that clarifies their relative value to building occupants. The hypothesis of this paper is concerned with identifying whether there is enough evidence available to relate benefits and risks already established by exterior application-based studies to interior applications. Addressing this will identify where focus is required to mitigate risks and enhance benefits, which in turn will ensure installations generate indoor environments that improve the health, wellbeing, and comfort of building occupants.

The background to vertical greening is addressed by reviews of exterior applications. This literature-base describes the approach as an intentional attempt to cover vertical built surfaces to a significant degree with plant life. Various authors have presented several terms to describe this principle, and a few have analysed common structures to distinguish categories and derived variants. Presently there is consensus on the distinct presence of two principal categories described as either 'green facades' or 'living walls', predicated on the location of the growth substrate [e.g. 2–4]. The growth medium in green facade features is either a limited ground area or contained in a planter that is located at the base of a host wall. The plants therefore root at the base and shoots grow up along the surface of the host wall; which is the reasoning for some authors describing such features as 'ground-based' greening [4]. Typical plants used for this purpose include climbers and wall-shrubs that represent a wide range in size, form, and phylogenetic origin. Presently, such ground-based green facades are experienced as exterior applications, while in interior environments vertical greening is dominated by living wall approaches.

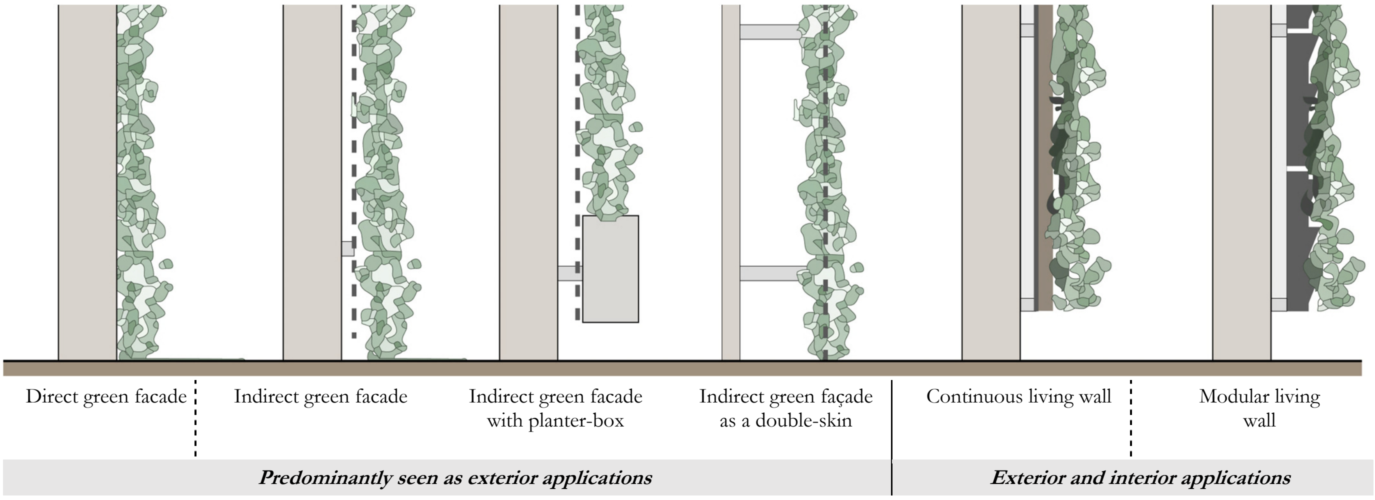


Fig. 1. Vertical greening categories and some exemplar variants.

Living wall approaches are a recent innovation that include the growth substrate on the vertical face of the host wall. The approach is referred to by some authors as 'wall-based' greening and is designed to allow the plants to root into a decoupled substrate carrying support-work that is tied back to a host wall [e.g. 4]. The systems used allow for water and nutrients to be delivered through embedded closed-loop irrigation and fertigation networks including automated monitoring and controls [5]. Depending on the application method, such constructions are further divided into the two types described as either 'continuous' or 'modular'.

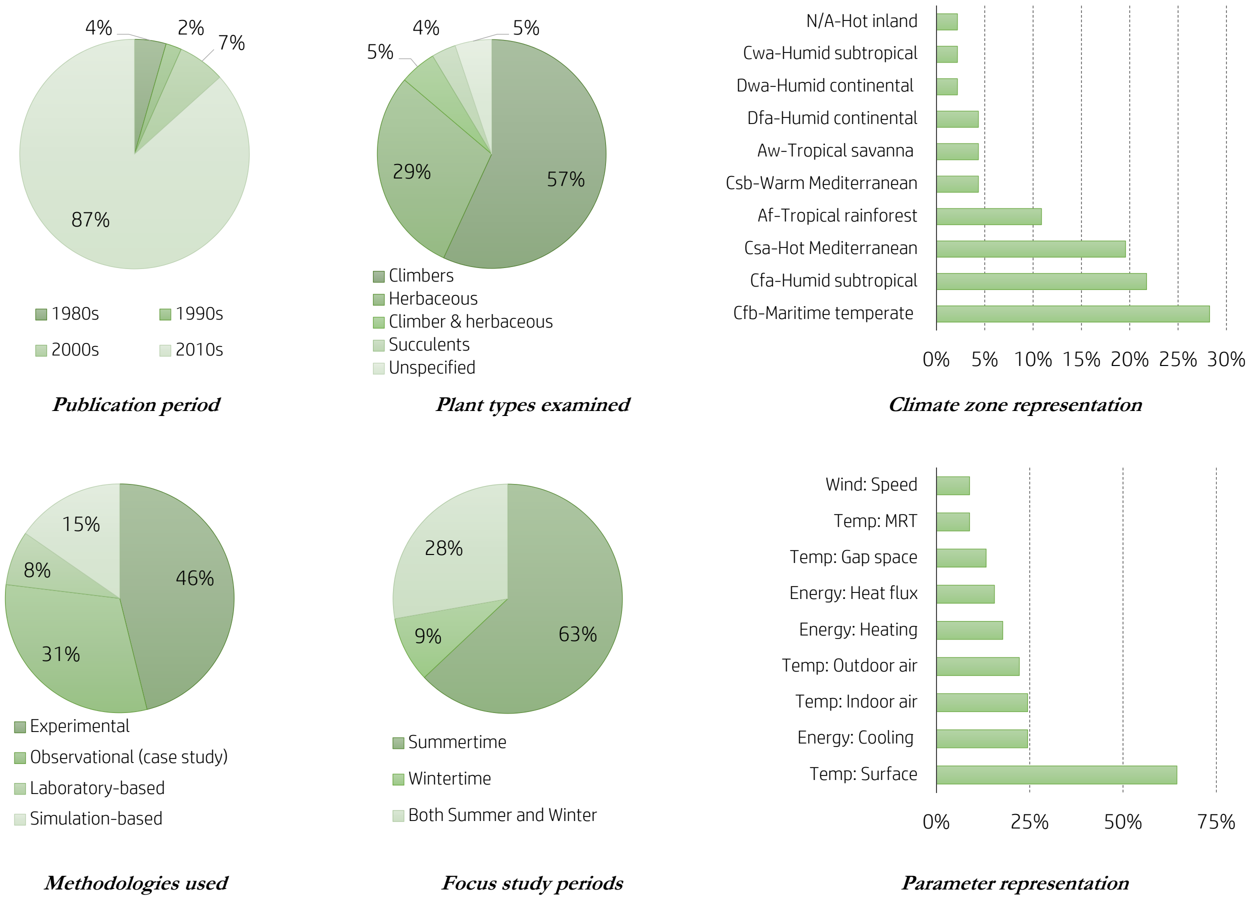
Continuous systems use a bespoke decoupled lightweight support skin into which plants are individually plugged onsite. The system approaches vary considerably with some using hydroculture felt or irrigation cloth [6]; some that use a deeper zone containing alternative substrates such as clay balls, peat chunks, peat moss, mineral wool, coconut fibres, etc.; and a few that use graded soils [5,7]. In contrast, modular wall systems use offsite manufactured interlocking cassettes or units to build-up a larger vertical surface area. Continuity of the arrangement is ensured by interlocking, which creates a tiled effect initially that visually mergers with subsequent growth. The units are made from lightweight plastics or metal and filled with either soil or alternative substrates as above. Unlike continuous arrangements, they are transported to site pre-planted and typically include several plants at an advanced stage of maturity. This in turn provides rapid assembly and if need be, disassembly benefit [3].

The application of such approaches within interior environments has encouraged adaptation and innovation. 'Bio-walls' for example represent a specialised variant of living wall (continuous or modular) that is adapted to passively enhance air quality aspects in indoor environments [1,3]. The specialist aspect of such systems is represented by the ecosystems cultivated, which include a diverse range of microorganisms and bryophytes, non-vascular plants that include liverworts, hornworts, and mosses. Lacking transport and woody tissue to support greater mass, these have limited growth extents and thrive in moist and reduced sunlight habitats that make them ideally suited for growth in most indoor environments [8]. Active living walls (ALW) represent a technical advancement of such walls that enhances air purifying services further by actively forcing air through a bio-wall filter [1]. They make use of the evaporative cooling potential of plants as well as their phytoremediation potential to purify and condition indoor air supply. This is expected to avoid or reduce the need for other mechanised filtration devices, which in turn could reduce indoor space-conditioning loads [9]. Another active soilless growth approach is aeroponics, where plants are grown without a substrate and within a nutrient-rich mist medium. This approach removes the load of a substrate zone and associated support, although includes active misting mechanisms that present specific maintenance requirements. This latter maintenance difficulty together with humidity control concerns have thus far prevented the integration of these approaches as scalable built-environment applications, despite this form of plant growth being used for many years in horticultural and agricultural practice.

Recent developments in living wall approaches has predominantly focused on enhancing system efficiencies. The research and development teams of suppliers have considered alternative growing media, irrigation, fertigation, drainage solutions, and remote monitoring and management systems to deliver efficient technical solutions in terms of performance, along with installation, maintenance, and replacement. Advancements in these areas have led to living walls being considered for a diverse range of building typologies and to varying degrees of scale and complexity. Such advancements have meant that these features are now being adopted for retrofit strategies in urban spaces as well as at building level exterior and interior applications [1,3,5,7]. Current research focus however is lagging, with preponderant interest for considering exterior as opposed to interior application assessments.

2. Methodology

This study principally considered the review of peer-reviewed journal publications from 1980 onward obtained through database keyword searches. The databases used included Scopus, Cambridge University Library, and Google Scholar; with the principal keywords used including ‘plants/vegetation’, ‘vertical greening’, ‘green facades’, ‘living wall’, and their variants using ‘interior/internal/indoor’ and ‘exterior/external/outdoor’ prefixes. These were then distilled to consider 44 papers that addressed the study of performance aspects of any form of vertical greening, be it experimental, case study, or simulation-based. Their principal subject background was built environment studies, and are represented in Fig. 2 according to publication decade, principal methodology used, parameter representation, and plant types examined. For certain aspects however, additional literature from plant sciences, acoustics, public health, and psychology had to be examined. The publication review was also supplemented by unstructured (with reference to general practice) and semi-structured (with reference to specific installations) interviews.



Publication period *Plant types examined* *Climate zone representation*

Methodologies used *Focus study periods* *Parameter representation*

Fig. 2. Breakdown of previous studies reviewed.

3. Findings and discussion

The review of studies highlighted the observations available as derived from examining predominantly exterior applications. These firstly try to determine the climates in which vertical greening approaches could generate and sustain a flourishing ecosystem, followed by the examination of their feedback to the climates they inhabit. The latter presents both benefits to human interaction with such features as well as certain risks. Built environment discourse however is focused on benefits than risks, with the discussion of certain risks confined to specialist knowledge areas that have yet to be integrated.

3.1. Local climate influence

The review of studies considering exterior vertical greening performance in cities highlights local conditions characterised by light, temperature, moisture, and wind climate as key determinants in generating and sustaining ecosystem service provision. Significant variance of such parameters determines stress responses, with extremes and exposure determining failure. With interior installations however, the climate encountered operates within a narrow band of variance relative to exterior conditions. This is particularly the case for conditioned buildings where interiors are maintained within an occupant comfort band that is equally suitable for the optimal growth of most plants [6]. Temperature related stress risk is therefore limited, with only localised stress from cold or warm draughts (e.g. from heaters) likely to cause failures [1]. Indoor humidity conditions on the other hand can present a moderate risk to plant health as these are generally maintained at lower levels to ensure occupant comfort (relative humidity/RH between 40-70 %). As some plant species selected for such interior installations (e.g. tropical shade-loving plants) tend to require high canopy humidity to maintain good foliage health (RH 85-95 %), comfort level RH may present the risk of foliage water stress. Vertical plant canopies however are observed to maintain a self-hydrating microclimate that mitigates this risk to an extent [6].

The most significant interior climate risk is low-light availability, which is factored when selecting species for indoor environments and often results in the inclusion of tropical shade-loving plants [1,5,6]. Typical indoor light intensity below 10 μmol PAR m^{-2} s^{-1} is likely to result in negligible efficacy in plant ecosystem service provision. It has been observed that horticultural light specifications which are much higher than this are also inadequate to ensure useful ecosystem service provision such as net CO_2 removal [10]. This may be overcome by the provision of artificial photosynthetically active radiation (PAR), although the approach could have a negative effect on energy saving and ecosystem benefits expected. It is also significant to note that low-light tolerant species exhibit lower photosynthesis and respiration rates [10]. This in turn influences the beneficial ecosystem feedback that can be reasonably expected.

3.2. Vertical greening feedback

Vertical greening feedback to the climate they inhabit presents their ecosystem benefits and risks. Studies characterise hygrothermal feedback influences by mainly examining the parameters of proximate air temperature and RH, and surface temperature; and to a lesser extent, with proximate wind flow modification. The following observations are derived from available exterior application-based studies, with discussion of probable variance expected with interior application.

3.2.1. Thermal

Exterior air temperature proximate to an installation is one of the most common parameters measured in the assessment of thermal influences, with measurements mainly taken relative to a control condition, and to a lesser extent with increasing distance from the host wall to assess effective range. The studies ranging from observational studies to modelling simulations suggest that the immediate air temperature modifications of vertical greening including direct, indirect, or living wall approaches to range between 0 and 3 K at most, while the effective range seldom exceeds 1 m from the wall surface [e.g. 8,11–16]. Higher performance has been demonstrated when conditions are drier and warmer (summer), relative to colder (autumn and winter) conditions [e.g. 15]. There is insufficient data amassed to suggest relative order between the different typologies, impact of widespread application, or significance relative to interior application. Greater influence however could be assumed in interior conditions, as restricted air movement is likely to aid in the detection and experience of temperature modifications.

Surface temperature is the most common parameter measured to assess thermal influence of exterior applications. Main measurements taken are of either the exterior foliage or substrate relative to a control condition. In general, research shows good representation across observational, experimental, and modelling approaches taken by the various studies dating from 1980 onward. In summary, they highlight significant surface temperature reductions resulting from greening presence (up to 30 K), with evidence of higher summertime benefit offered by living walls relative to green facades [e.g. 11,17]. The limited wintertime studies available indicate that green facades could provide a beneficial warming influence [e.g. 18–20], while living walls provide significantly lower benefit [e.g. 21]. Across all typologies, these effects seem to be most pronounced on the harshest of days in both summer and winter, with cooling performance during the daytime and a potential warming influence during the night-time likely [e.g. 19,20,22–26]. No significant observations or results are presently available for interior applications, although the reduced incidence of solar radiation could be assumed to present much lower surface temperature variance.

Studies demonstrate that the application of vertical greening to exterior wall surfaces increases the thermal buffering of the exposed envelope to improve indoor comfort, with potential to reduce cooling loads [e.g. 27–32]. The investigation of such thermal effects when vertical greening is applied within an indoor environment however needs greater attention. An exception was presented by a recent laboratory-based study by Pérez-Urrestarazu *et al.* [9] of an active living wall (ALW), where they found its cooling efficiency to be at its best when the initial room conditions were drier and warmer, which agrees with studies of exterior applications. Although the cooling extent gained by this interior application was relatively modest, the benefit still presented potential for energy savings by reducing cooling load demand.

3.2.2. Moisture

Vertical greening is identified to contribute a bio-protective moderating moisture influence, which is characterised in studies with RH measurements mainly taken relative to a control condition, and to a much lesser extent with increasing distance from the host wall to assess effective range. With reference to exterior green facade applications, Sternberg *et al.* [18] found this humidity moderating effect to be less than surface temperature moderations observed. Susorova *et al.* [13] found RH to be higher inside vegetation layers, although the absolute humidity to be unaffected. The latter suggests that RH is increased by the cooling of the foliage air temperature, while the humidity produced by transpiration may be utilised to maintain good foliage health during summer conditions. This self-generating humid microclimate therefore assists in sustaining good plant health [6], which is significant for indoor climates where humidity is typically maintained at lower levels to aid comfort.

Beyond the foliage zone the influence range of the humid microclimate is expected to decay, although little quantitative evidence is published to support and characterise this decay at present. An exception is provided by Blanc [6] where he reported RH to decay from 90 % at 50 mm; 80 % at 100-200 mm; 70 % at 300-500 mm; 60-65 % at 1 m; and normalise at 59 % ambient humidity around 1.5 m away from the hydroculture felt of his Mur Vegetal living wall system. More data however is needed to clarify influence in relation to indoor conditions, as potential for increasing humidity levels is a risk to both occupant thermal comfort and health.

3.2.3. Wind flow

Vegetation canopy studies have demonstrated their increased roughness to exert mean flow transformation by introducing mechanical turbulence. The resulting eddies enhance the sensible and latent flux of their surfaces, irrespective of temperature and vapour gradients [33]. The introduction of surface greening can be expected to enhance a building's interaction with mean flow further by increasing its micro-scale surface roughness. Such wind flow modifications however represent the least investigated aspect of surface greening feedback. When assessed, it is typically characterised by surface proximate flow velocity measurements taken relative to a control condition, and to a much lesser extent with increasing distance from the host wall to assess effective range. The available observations at present are exclusively of exterior applications and these show mean flow reductions to vary between the categories and their variants [13,17]. Perini *et al.* [17] identified that the lower wind velocities observed in the foliage zone (<0.2 m s^{-1}) could be used to equate exterior surface resistance with interior resistance, which in turn affects the total thermal resistance calculation of the envelope to present potential energy savings. In dense foliage canopies, the reduced mean flow above the canopy is exponentially reduced within the canopy zone [17,34]. As wind velocity has an inverse relationship with boundary layer thickness, which in turn has an inverse relationship with boundary layer conductance, leaves within canopies are observed to have lower boundary layer conductance and as a result are poorly coupled with the atmosphere. In such conditions transpiration efficiency will be mostly driven by radiation incidence [34]; which in turn is reflected in the diurnal pattern of cooling observed. This suggests that in indoor conditions where radiation incidence is restricted, thicker canopies are likely to be less effective in delivering the transpiration cooling benefits expected.

The relatively cooler surface presented by vegetation could be hypothesised to generate cold radiation effects and the formation of a 'downdraught effect' resulting from natural convective boundary layer flows along the surface. Such cold surface effects are well-documented in indoor environments, with studies mainly addressing occupant discomfort arising from proximity to cold window surfaces [35]. Manz & Frank [36] found such draughts to be critical for discomfort relative to reduced operative temperatures or radiation asymmetry, while Heiselberg [35] found discomfort to rapidly decrease within the first 2 m off the surface to highlight its decay. The potential relevance of such surface temperature influences however has not been assessed in relation to vertical greening surfaces. With exterior conditions such effects are likely to be detectable only under stable conditions with very low wind velocities, as at higher velocities turbulent mixing could rapidly normalise such micro-scale effects. With indoor conditions however, there is greater potential for convective boundary layer flows to develop and cold radiation effects to be detected. Depending on the magnitude and pattern of decay, such influences could either threaten or benefit building occupant thermal comfort, and thus warrants further investigation.

Fig. 3. André Hoffmann Atrium living wall at the David Attenborough Building in Cambridge.

3.3. *Building energy use implications*

Hygrothermal feedback from plant cover and its influence on building energy use has been well-established by horizontal greening studies. Similarly, available vertical greening studies focusing on exterior applications have highlighted the modification of surface temperatures to affect climate thermal load transfer or wall flux into interior building environments. This wall flux represents a substantial contribution to interior space-conditioning loads and resultant energy use [37], although the extent of transfer is dependent on the envelope build-ups examined [21]. Generally, flux reductions are evident across the different vertical greening typologies, exemplified by the green facade study presented by Susorova *et al.* [13], grass-based living wall study presented by Cheng *et al.* [38], and the Mazzali *et al.* [39] study of three living walls that also measured outgoing flux to identify an enhanced latent flux or envelope cooling effect.

Space-conditioning is mainly discussed in relation to exterior application influence on interior summertime cooling loads. This is influenced by the evidence discussed earlier in relation to optimal surface cooling benefits being evident during this period. There is preference for this hypothesis to be investigated using simulation studies, with simulations by Stav & Lawson [40] and Kontoleon & Eumorfopoulou [32] for example having estimated reduced indoor temperatures, better thermal comfort, and reduced cooling loads. The dominant preference however is for using experimental design, with many examples presented for the different categories and their variants identifying cooling energy savings. As examples, the direct green facade study by Susorova *et al.* [13] reported small savings from the solar shading effect and additional savings from reduced air infiltration, while the double-skin indirect green facade study by Pérez *et al.* [26] reported main savings from east and west orientations to stress solar shading influence, and the grass-based living wall study by Cheng *et al.* [38] attributed savings to the lower and delayed heat transfer (i.e. enhanced thermal resistance and inertia) of the wall build-up. From these studies, a direct correlation between solar irradiation and energy savings is generally observed to suggest higher relative cooling energy savings in climates with high irradiance [25]. Given the limited influence of radiation incidence in indoor conditions, the energy saving potential from the canopy shading effect could therefore be assumed to be minimal.

The few studies that have considered the annual effects of exterior applications have recorded a moderating effect with colder winter temperatures to highlight thermal benefit. Observational studies by Bolton *et al.* [19] and Cameron *et al.* [20] for example identified the insulating and shielding thermal benefits offered to reduce winter heating loads, and also highlighted greater performance with increased cover and during relatively harsher conditions. The studies therefore recognise wintertime benefit in addition to summertime cooling savings principally stressed. This however is better supported by green facade observations, while more evidence is required for living wall conditions with some winter studies having reported significantly lower savings [25]. With reference to green facades, current research presents reasonable evidence for justifying their use as a thermal enhancement strategy, which may be particularly useful as retrofit solutions for older buildings where other options may be unsuitable [8,20,41]. In indoor environments however, the shielding effect is likely to have little to no influence on space-conditioning, while the insulating effect could contribute to interstitial condensation risk dependent on the build-up involved.

The review found no studies to quantify energy use implications of the interior application of vertical greening. Interior conditions could be considered as analogous to a greenhouse, where seasonal dependencies are controlled to offer continuous growth and ecosystem service provision throughout the year. The cooling benefit expected during the summer is likely to offer reduced building cooling loads as suggested by the Pérez-Urrestarazu *et al.* [9] study. In winter however, continued growth and resultant cooling from typically evergreen cover could present a negative hygrothermal influence. When considering interior application influence on energy use, annual space-conditioning loads must therefore be assessed to determine net influence.

3.4. Carbon sequestration

The uptake and long-term storage of CO_2 is described as carbon sequestration, which represents a significant feedback benefit of plant cover.

Photosynthesis:

$$6CO_2 + 6H_2O + K^*(solar\ radiation) = C_6H_{12}O_6\ (Glucose) + 6O_2 \tag{1}$$

Plants remove atmospheric CO_2 by photosynthesis to create biomass, and thus are natural carbon sinks. Like all green-space features, vertical greening also provides this valued ecosystem service, although the relative significance of which is not well quantified by current research [20]. The recent study by Marchi *et al.* [42] presents an exception, where they estimated that for a 98 m^2 living wall CO_2 capturing was between 13.4 and 97 kg CO_{2eq}. Plant selection was identified as significant for this sequestration efficacy, with CAM plants of the genus *Sedum* showing relatively poor performance compared to C4 grass and C3 herbaceous plants [42], while Charoenkit & Yiemwattana [30] highlighted a woody plant as performing better relative to the evergreen herbaceous plants examined. Charoenkit & Yiemwattana [30] also noted performance to be dependent on stress, with poor sequestration observed from summer heat and water stress. In indoor environments where stress conditions are relatively well managed, the air purification benefit from CO_2 uptake is likely to be significant.

3.5. Improving air quality

In addition to CO_2 uptake, plants have long been observed to capture a variety of pollutants, and even partly metabolise or bio-transform them with the aid of microorganisms that coexist in their microbiome. Plant phyllosphere surfaces such as leaves and stems, adsorb significant amounts of such pollutants. A proportion of this also enters the plant through stomatal pores, while some of the surface residual may be washed down with rainfall and added to the soil below to facilitate contact with the rhizosphere. In both the phyllosphere and rhizosphere, microorganisms such as bacteria and fungi perform the beneficial function of detoxifying pollutants by the means of degradation, transformation, and sequestration pathways. The use of plants and their microbiome to remove, detoxify, or immobilise contaminants is described as 'phytoremediation', and has long been used in decontamination practices. Interest in phytoremediation for air-purification peaked during the 1980s, following several projects by NASA considering closed-system applications for use in space-stations [43]. Since then numerous studies have replicated findings to suggest potential for wider applicability, with removal action typically assessed in terms of the three groups of particulate matter (PM), volatile organic compounds (VOCs), and inorganic pollutants.

Particulate matter represents a diverse range of airborne solids and liquids that are categorised based on their aerodynamic diameter. They are generated naturally by processes such as erosion, and by various anthropogenic activities such as combustion. The diversity of their origins, forms, and chemical compositions mean that toxicity also varies, although evidence suggests that this pollutant represents one of the most hazardous to human health [44]. In addition to climate conditions such as precipitation and wind, and PM quantity and composition, plant capturing capacity is influenced by species-specific features like canopy morphology, and leaf size, ultrastructure, thickness, surface roughness (presence and density of trichomes or pubescence), and the chemical composition and structure of epicuticular waxes. Electrostatic forces play a role in attracting PM [6], while the epicuticular wax layer immobilises and stabilises adsorbed

PM [45]. This physical means of PM removal is described as dry deposition, where the particles impact upon and stick to surfaces [46,47]. Studies that consider dry deposition have mainly examined outdoor environments, with examples from Ottelé *et al.* [48] and Viles *et al.* [49] finding high urban PM_{10} deposition with higher deposits on leaf topside. In contrast, an indoor study by Pegas *et al.* (2012) found daily PM_{10} levels in a classroom to be higher than outdoors, although with the addition of potted plants these concentrations were reduced by 30 %. Such observations support PM capturing services offered by plants and their effective action in both outdoor and indoor environments [51,52]. Alongside the physical features that assist with PM capturing, microorganisms associated with their microbiome are significant in implementing degradation and metabolic pathways. These are mainly implemented in the rhizosphere, with root endophytes identified to utilise a metal-resistance sequestration system to decrease PM attached metal toxicity, and enhance tissue bioaccumulation [53]. Similar action on leaf surfaces might be expected by phylloplane microorganisms, although little research is available to support this hypothesis [54].

VOCs are described by their physical and chemical characteristics such as boiling range and vapour pressure, and carbon number. The most referenced are Toluene, Ethylbenzene, and Xylene (TEX); Benzene; Poly Aromatic Hydrocarbons (PAHs); and formaldehyde [54]. They are produced by anthropogenic activities such as transport or industry, and by biogenic activities of plants [55]. Various materials and industrially processed products such as carpets, wallpaper, curtains, paper products, and electronic equipment emit VOCs, with newer materials emitting highest concentrations [56]. They are hazardous to human health with recorded short and long-term effects, including multiple chemical sensitivity and a range of symptoms characterised as 'sick building syndrome' [57]. Removal action from plants is exemplified by Pegas *et al.* [50], where they found potted plants to reduce indoor concentrations. This VOC uptake is principally achieved through leaf stomata, with the residual contribution from surface cuticle and rhizosphere. In dry conditions, VOCs penetrate the soil and are degraded by the more efficient degradation system functioning in the rhizosphere [43,54]. Wolverton *et al.* [43] stressed that as the rhizosphere is the most effective removal area, maximizing air exposure to this area should be prioritised. As plants are a source of VOCs, when selecting them for phytoremediation use the net effect must be considered. The Dela Cruz *et al.* [58] review is an example where over a hundred indoor plant species were reviewed for their net removal capacities.

The most common inorganic air pollutants are Carbon dioxide (CO_2), Carbon monoxide (CO), Sulphur dioxide (SO_2), Nitrogen oxides (NO_x), and Ozone (O_3). Ozone is formed when solar (UV) radiation induces photochemical reactions between NO_x, VOCs, and CO, while the rest are mainly added to the atmosphere from combustion processes. In high concentrations such inorganic air pollutants cause adverse effects to plants, although some species are more tolerant and sink these by bioaccumulation in tissue. The Weyens *et al.* [54] review stresses that less is known about the significance of the plant-associated microbiome in inorganic phytoremediation. With carbon sequestration, it is known that the microbiome affects humus formation, although the potential contribution of mycorrhizal fungi is not well-addressed. They hypothesise that the microbiome could be involved in some NO_x and SO_2 capturing, although little evidence is currently available. Ozone in contrast is a known antimicrobial agent, thus the contribution of the microbiome is likely to be associated with toxicity reduction [54].

Table 1.
Inorganic pollutant removal action from plants.

Inorganic pollutant	**Removal action**
CO_2	Removal from photosynthesis (Eq. (1)). For example, Pegas *et al.* [50] observed potted plants to reduce indoor mean CO_2 concentration by 44 %.
CO	Plants metabolise CO by oxidation into CO_2 or by reduction and assimilation into the amino acid Serine. Bidwell & Bebee [59] experiments identified CO as showing mixed influence on photosynthesis, ranging from inhibition at low concentrations, increased net fixation at very high concentrations, and no influence in some cases. This means that in urban areas where high CO concentrations are typical, plant uptake of CO could be significant [59].
SO_2	Modest concentrations can be a sulphur source. After entering through stomata following the same pathway as CO_2, it may be utilised in a 'reductive sulphur cycle' to form amino acids needed for growth and development [60].
NO_2	Removal occurs mainly by stomatal uptake to the apoplast and secondly by adsorption to leaf and root surfaces. Mostly metabolised through the nitrate assimilation pathway into compounds like amino acids [54].
O_3	Removal achieved mainly by absorption through stomatal apertures, and secondly by cuticle adsorption when surface moisture is available. Readily decomposes when reacting in the gaseous-phase or when impacted by cuticle or apoplastic compounds, although less is known about what occurs after stomatal entry [54].

A key advantage of living walls over other greening strategies is the enhanced coverage and planting density offered, which maximises the provision of vegetation related ecosystem services for a given footprint. This is illustrated by a study considering CO_2 removal with Bamboo palm (*Dypsis lutescens*), where it was shown to require the impractical use of 249 potted plants to offset the respiration output generated by an average human occupant in an unventilated room (average exhalation of 34.5 mg CO_2 h^{-1}). It was estimated that to offset this output would require around 57 m^2 of leaf area, which could be addressed by around 5 m^2 of living wall coverage [61]. A key requirement for maintaining the efficiency of this purification ecosystem service however is good plant health. A recent laboratory study by Rondeau *et al.* [62] for example highlighted that although a planted biofilter was able to remove low concentrations of pollutants, the addition of nutrient solution was essential for maintaining this pollutant degradation efficiency. Interior bio-walls are therefore likely to require greater attention to ensure effective and sustained air-purification services.

3.6. Acoustics

Plants attenuate noise by absorbing, diffracting, and reflecting sound. Vegetated installations have as a result been widely used as means to improve outdoor and indoor sound environments [4,63]. Experimental vertical greening studies by Wong *et al.* [64] found stronger attenuation at low-to-middle frequencies owing to a substrate absorbing effect, with smaller attenuation at the high frequency spectrum owing to foliage scattering. The systems examined exhibited highest sound absorption coefficients relative to other materials, with absorption coefficients positively correlated with frequencies and plant coverage [64]. Laboratory studies by Davis *et al.* [65] also noted that living walls correspond to the behaviour of porous absorbers with low absorption evident at lower frequencies and high absorption at higher frequencies. To improve acoustic performance, parameters such as mass (thickness and composition of substrate and vegetation), impenetrability (sealed joints, [e.g. 66]), and structural insulation (support structure) requires greater attention [63]. Performance is also dependent on plant growth stage and health [67]. As these observations are mostly based on laboratory-based studies, the findings presented could be argued to be relatable to both exterior and interior applications.

3.7. Biodiversity

From the few available urban biodiversity studies that address surface greening, the majority have examined green-roofs to identify enhancements in diversity and population abundance of flora and fauna [68,69]. Notable earlier work on green facades include a study by Benedict & McMahon [70] that identified greater presence of birds, and the thesis by Matt [71] that found between 16 to 39 times more collections of diverse arthropods. A recent study of thirty-three sites in Paris by Madre *et al.* [72] characterised green facades as 'xerothermophilous' habitats comparable to cliffs, while continuous felt and modular substrate-filled living wall types were characterised as damp and cool habitats comparable to vegetated waterfalls. The latter modular system with its increased substrate depth was found to offer the highest diversity and abundance of species [72]. Such surveys however are currently available only for exterior applications, where the ecosystems are exposed to migration influences and interactions with the wider context. Biodiversity at interior applications in contrast is likely to be significantly limited owing to the restricted ecosystems created, with introductions most likely at planting or replanting stages. Further attention is needed to identify the diversity present and sustained at such installations, as well as the nature of their interactions (favourable or otherwise) with building occupants. Biodiversity potential must also be considered in relation to other services including pollination, biological control, and decomposition (microbial diversity).

3.8. Wellbeing and restorative impact

The natural setting including plant life is identified to increase positive distractions and emotions, promote restoration from illness and stress, and enhance the sociocultural climate [73,74]. The contribution of plants to the aesthetic and wellbeing enhancement of cities is acknowledged in built environment discourse as biophilic design, which gathered interest and momentum in response to the need to alleviate symptoms of sick-building syndrome [68]. One school of thought based their argument on plant services that offered physiological benefits to building occupants, particularly in relation to their ability to purify air and enhance microbial diversity [75,76]. The alternative school of thought had based their argument on the psychological associations made by building occupants. This was established by early health restorative studies from Ulrich [73,77] and 'attention restoration theory' by Kaplan & Kaplan [78], which promoted the natural environment including plants as having a restorative effect on attention, wellbeing, and health.

Following early work by Ulrich [73] and others, recent health restorative studies present supporting evidence for plants to be used in healthcare facilities as a supplementary healing incentive [e.g. 74,79,80], with Dijkstra *et al.* [80] notably identifying the perception of attractiveness offered by plants as a key influence. Kaplan & Kaplan [78] had argued that the presence of a natural setting with plants to offer stimulation that does not demand exhaustive directed or focused attention, but in contrast to trigger undirected attention or 'soft fascination' to encourage the restoration of attention capacity. Raanaas *et al.* [81] for example found significant performance improvements following exposure to potted plants, while a recent study of classrooms by van den Berg *et al.* [82] presented one of the first studies to have considered an indoor living wall, with results of better scores for selective attention and classroom evaluations positively influenced.

Examining such plant influences has progressed significantly with the greater understanding of biochemical processes of human physiological and psychological responses. A body of studies as a result had branched-off to combine the assessment of psychological responses with associated physiological indicators. In such studies, physiological indicators such as heart rate and pulse variability, blood pressure, skin moisture conductivity, hormone concentrations such as cortisol and cortisone, and oxyhaemoglobin concentrations in the prefrontal cortex, are quantified to characterise conditions of participant anxiety or stress. These are then related to psychological responses characterised by subjective responses from 'semantic differential' (SD), 'profile of mood state' (POMS), or other questionnaires [e.g. 83–85]. Notably, such a study by Yin *et al.* [85] validated Dijkstra *et al.* [80] findings to indicate the primacy of visual perception in affecting positive psychological influences. Living wall installations in this regard present significant potential for greater visual and physical interaction owing to their unavoidable vertical presence, with proximity and exposure influence likely to be greater with indoor installations. However, save for the recent attempt by van den Berg *et al.* [82], the study of indoor living wall influence on restorative impact is very much in its infancy.

3.9. *Potential risks to consider*

While most biogenic processes of plant life could be considered as beneficial influences, some aspects can present challenges to human comfort and health. These include plant VOC emissions discussed earlier, CO_2 emissions from respiration, humidity modifications, and release of pathogens, allergens, and toxins.

Respiration:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + Q_{res}\ (Combustion) \tag{2}$$

As discussed earlier, CO_2 is an essential ingredient of photosynthesis and plants reduce atmospheric concentrations to provide an air purification service that is particularly useful in indoor environments. The Irga *et al.* [61] study for example, recorded a concentration reduction of 214 mg of CO_2 per m^2 of leaf area per hour from the houseplant Nephthytis, while the Torpy *et al.* [10] study measured the highest reduction of around 657 mg CO_2 m^{-2} h^{-1} from Bamboo palm. These removal rates are dependent on species-specific photosynthesis rates and efficiency, as well as light levels and temperatures experienced. Low light level conditions reduce photosynthesis rates and the resulting net effect of CO_2 removal. In certain situations, this could lead to increased CO_2 concentrations aided by contributions from continuous respiratory CO_2 emissions (Eq. (2)) from non-photosynthetic plant organs and the microbiome, and photorespiration resulting from photosynthesis inefficiencies [61]. As most plants do not photosynthesise in darkness (except CAM plants), continuous plant respiration dominates at night to add CO_2 to the atmosphere. This in turn could become an air pollutant (mild narcotic) that affects the nocturnal health and comfort of inhabitants in poorly ventilated spaces. However, the concentrations involved in most indoor environments including plant life are likely to be dissipated by the presence of some degree of background air infiltration and ventilation.

As discussed earlier, humidity from evapotranspiration is a significant microclimatic influence generated by plant feedback. Increases can have an adverse effect on human health by promoting the growth of adverse microbial activity, and by hindering efficient thermoregulation to cause discomfort. Previous studies examining indoor conditions had demonstrated humidity levels to increase with the addition of potted houseplants, although had substantially less capacity than amounts generated by other devices to cause harm to health or comfort [76,86,87]. Potted plant humidity influence on pathogenic microbial growth had also been identified to fall short of the concentrations necessary for colony forming units (cfu), with their microbiome potentially preventing airborne pathogenic colony growth by releasing inhibiting allelochemicals [87]. These findings however must now be reassessed in relation to the greater plant coverage presented by living walls.

Pollen, spores, and other plant matter are also significant allergens that can cause individual-specific reactions. The limited allergy studies available highlight allergen concentrations in outdoor environments to be much greater than indoors, although increased indoor occupation increases exposure risk. Studies assessing this indoor risk have thus far considered only typical houseplants [e.g. 88]. The allergenic aspects of vertical greening plants are not discussed in current research, although an increased risk from indoor living walls may be expected owing to increased abundance and diversity introduced. Exterior vertical greening approaches adjacent to ventilation inlets or windows also present the potential for allergens entering indoor air circulation, as plant allergens have been found to transport, even across vast distances [88].

Plants also produce various toxic compounds that can be distinguished as either relevant for plant metabolism or residuals. It is hypothesised that during the evolution of metabolic pathways such compounds may have been produced as by-products, and the failure to expel these from the plant system had resulted in these existing as toxic residuals; with some species repurposing this toxicity as defence mechanisms against herbivorous attack [89]. Examples of toxic compounds found in typical houseplants include Alkaloids, Cardiac Glycosides, Colchicine, Diterpene Esters, Grayanotoxins, Oxalates, Polyacetylenes, Protoanemonin, and Tannins [90]. These may have adverse physiological impact on both humans and domesticated animals. The effects usually result from ingestion of significant quantities, or dermal or ocular contact for significant durations. The human reactions that arise from such toxins range from dermatitis following dermal contact, gastrointestinal upset from ingestion, to more acute reactions including cardiac or respiratory failure that could lead to death. Children and smaller domesticated animals in particular show higher vulnerability to such adverse toxicity reactions [90]. Acknowledging these vulnerabilities and high-exposure risk to building occupants has encouraged plant toxicity research to focus attention on well-known houseplants. However, the potential risks from indoor living wall presence is not currently addressed. This is significant to consider given the desire to include exotic shade-loving tropical plants at such installations, and the potential for their resulting adverse reactions being unfamiliar to attending medical practitioners.

Various studies from plant sciences have examined the above discussed adverse modifications to identify some degree of risk to inhabitants from including plant life in the built environment. It is significant to note that most built environment focused studies advocating plant inclusion at present seem to discuss such risks cursorily, with research addressing risks in relation to specific applications such as indoor living walls as notably lacking. Future attention should also target specific building typology risks, with residential buildings likely to be of greater significance due to proximity and exposure risk from dominant occupation, while schools and hospitals may present heightened risk owing to dominant occupation by vulnerable groups. Hospitals in particular are a challenging typology to consider, where established restorative benefits would have to be balanced against potential health risks.

4. Conclusion

Exterior application-based studies assessing thermal influence present evidence to suggest that vertical greening belonging to both categories offer significant benefit, with cooling influence during summer and in some instances a warming insulating effect in winter; with improved performance when conditions are at their harshest. There is some evidence to suggest better performance in drier, warmer climates, with more evidence required to justify claims for cooler temperate climates. These thermal enhancements in return have been established to offer summer cooling and winter heating energy use benefits to buildings, although the body of evidence is biased towards emphasising summertime benefits. This is explained by the acknowledgment of preceding plant science observations that validate optimal vegetation ecosystem service provision including carbon sequestration, air purification, acoustic, biodiversity, and wellbeing and restoration enhancements to be pronounced during the active summer period.

The above observations derived from exterior application studies need to be reassessed in response to how they relate to interior climate performance, which at present is at a state of infancy. Given that exterior application studies attribute radiation incidence and associated plant canopy shading to significantly contribute to enhanced thermal performance, suggests that in interior climates their thermal performance is likely to be represented greater by the less potent contribution from evapotranspiration. The limited evidence available suggests that this contribution could still be beneficial for reducing cooling loads in summer, although no evidence is available for winter performance and how this might influence net annual space-conditioning. The assessment of annual performance is highlighted as significant as the plants used in interior applications are typically shade-loving, tropical, and evergreen, and able to provide ecosystem services throughout the year. This annual consideration is also applicable to the examination of other ecosystem services including carbon sequestration, air purification, acoustic, biodiversity, and wellbeing and restoration influence, where more evidence is necessary to assess the relative significance of introducing greater plant coverage and diversity, which distinguishes living walls from other forms of indoor greening previously experienced.

Table 2.
Knowledge gaps and research potentials.

Knowledge gaps	**Future research potential/direction**
Relative significance of hygrothermal feedback	Annual monitoring studies including influence decay; including both mechanically and naturally ventilated buildings; particularly in temperate climates.
Wind flow feedback	Potential for cold radiation or downdraught effect.
Building energy use significance	Annual monitoring; emphasis on winter energy use impact.
Biodiversity sustained	Longitudinal surveys, including assessment of the nature of interactions with building occupants.
Wellbeing and restorative impact	Influence of coverage and different building uses.
Phyto VOC emissions, pathogens, allergens, and toxins	All such aspects and their relative influences have yet to be addressed in relation to indoor living wall coverage and diversity enhancements.

Although the exterior application-based evidence base can be related to interior applications to a certain degree, the specific study of interior applications is required to justify the value of ecosystem services they generate. This call for further study is highlighted as pertinent given that much of human habitation in cities occurs within indoor environments, thereby providing greater opportunity to enhance building occupant health, wellbeing, and comfort. Some of this attention should also be directed at examining potentially adverse plant-related modifications, which to date has received little to no attention from built-environment-focused studies. This paper therefore identifies the necessity for future research to consider and integrate such plant science aspects to provide a sound evidence base for the increased inclusion of indoor living walls in urban built environments.

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