INTERNATIONAL JOURNAL OF ACADEMIC RESEARCH IN BUSINESS & SOCIAL SCIENCES
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ISSN: 2222-6990

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To Link this Article: http://dx.doi.org/10.6007/IJARBSS/v13-i7/17965 DOI:10.6007/IJARBSS/v13-i7/17965

Received: *12* May 2023, ***Revised:*** *13* June 2023, ***Accepted:*** *29* June 2023

Published Online: *17* July 2023

In-Text Citation:(Ghazalli et al., 2023)

To Cite this Article: Ghazalli, A. J., Brack, C., & Ghazalli, A. J. (2023). Improving Indoor Environmental Quality—Measuring the Potential Contribution of Vertical Greenery Systems. *International Journal of Academic Research in Business and Social Sciences*, *13*(7), 1819 – 1843.

Vol. 13, No. 7, 2023, Pg. 1819 – 1843

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ISSN: 2222-6990

Improving Indoor Environmental Quality— Measuring the Potential Contribution of Vertical Greenery Systems

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Abstract
A structure is taken to be a green building if it benefits the environment, people, and the economy. For a building to be ratified as green, the building owners must adhere to specific guidelines and requirements. A green building involves using sustainable practices from construction to completion, as well as having long-term positive effects on users and the environment. Retrofitting vertical greenery offers various benefits, such as increasing indoor air quality, and is an attractive and effective way of achieving green building rating points. This study adopts an integrative review methodology to assess, analyse, and synthesize the current literature, and highlights the potential of green retrofitting for improving indoor environmental quality. The requirements for three green building certification schemes were reviewed and it is concluded that vertical greenery (outdoor and indoor) can potentially contribute to give value/points of the indoor environmental quality rating criteria that are used. The findings also indicate that, vertical greenery is applicable for retrofitting existing or conventional buildings, so they meet green building certification.
Keywords: Green Building, Green Wall, Sustainable Cities, Environmental Quality, Retrofit.

Introduction

The rapid increase and the high population densities associated with inappropriate urban development and planning have led to problems such as air pollution, flash flooding, and mental health issues (Jackson, 2003; Taylor & Hochuli, 2015). The migration of people into cities now means that more than 50% of the world's population resides in urban areas and the figure is projected to reach 68% by 2050 (WHO, 2021). Climate change also has an impact on urban living. The repercussions of climate change are not only on the economy, physical property, and the ecosystem, but also have an impact on human physiology and population health (McMichael & Lindgren, 2011).

To ensure that development in cities benefits everyone, it should be guided by a proper urban planning framework. An urban planning framework should focus not only on the form and economic benefits associated with cities, but also on the health and social aspects of city development. A city such as Canberra, Australia, has used five themes in its planning strategy: compact and efficient, diverse, sustainable, resilient, liveable, and, finally, accessible (ACT Government, 2019). Biodiversity and ecosystem management have also been found to be important elements in ensuring human well-being in urban areas (Taylor & Hochuli, 2015).

In addition to the outdoor environment, the interior environment also warrants attention as people spend substantial time indoors (for living, work, and education). The interior environment is enclosed within the building envelope and its insulation, contains furnishings, and is supported by air-conditioning, all of which can be sources of pollutants (Jasmin et al., 2012; Ballester et al., 2009). Poor ventilation systems may cause air pollutant concentrations to be higher indoors than outdoors. Active building management or refitting—such as the use of indoor finishes and materials that do not emit harmful gases and improved ventilation in conventional buildings (MacNaughton et al., 2016)—can help alleviate these problems. The use of natural elements can positively influence the health and well-being of the building occupants. Studies on interior green infrastructures such as indoor vertical greenery systems (iVGS) showed various positive contributions such as decreasing temperature (Poórová et al., 2020) and filters air pollutants while increasing aesthetic value (Wang et al., 2016).

In this paper, we discuss the importance of providing an acceptable interior environment, and set out green building objectives, methods, and measures of success. We focus on indoor environmental quality (IEQ) by presenting and comparing three existing guidelines: Leadership in Energy and Environmental Design (LEED) v4 for Building Design and Construction, which is used worldwide; the Green Building Index (GBI) Assessment Criteria, used in Malaysia; and the Green Star Rating—Design & As Built, which is used in Australia. We give a summary of how the use of vertical greenery systems (VGS) translates into the green building ethos. The central theme is to assess whether existing buildings can benefit from these new building approaches. Our final recommendation involves an assessment of the feasibility of retrofitting iVGS to increase IEQ.

Interior Environment

For people that spend many hours indoors, comfort is an important factor that influences well-being. Comfort is largely affected by indoor temperature and humidity. Other factors that enhance the interior environment include air quality, visual quality, acoustic properties, and lighting. An acceptable interior environment promotes general health, productivity, job satisfaction, and reduces stress (Danielsson & Bodin, 2008; Li & Sullivan, 2016; Menzies & Wherrett, 2005). Even a small decline in indoor comfort can negatively impact performance (Al Horr et al., 2016). Previous studies have identified factors such as space design and arrangement, the presence of plants, visual access to views through windows, the presence of wall posters (abstract or natural), and even having animals such as fish to make a space feel more comfortable and welcoming, all increase attention and reduce stress (Bringslimark et al., 2011; Kweon et al., 2007; Raanaas et al., 2011; Shoemaker et al., 1992).

The quality of the interior environment is affected by indoor air quality (IAQ). Cool and dry air is perceived as more acceptable compared to warm and humid air (Fang et al., 2004). If humidity levels exceed 50%, the air quality is unsatisfactory (Fang et al., 1998). Poor ventilation, the use of finishes that emit harmful gases such as volatile organic compounds (VOCs), dust accumulation (via outdoor sources or indoor tobacco sources), as well as allergens and airborne fungi can negatively impact IAQ (al horr et al., 2016; G. Liu et al., 2017).

To ensure acceptable IAQ levels, there are several measures that can be undertaken. Ventilation has been referred to as an important factor in acceptable IAQ, followed by managing pollutant source (Al horr et al., 2016). However, IAQ is also largely influenced by outdoor air quality because increasing ventilation brings outdoor air inside. Therefore, using air filters is an important step as it helps remove air pollutants; it is also cost effective as it helps with energy saving (Liu et al., 2020). One review has pointed out that a combination of filtration technologies is needed to provide a sustainable and healthy interior environment (Liu et al., 2017); the reason being that, despite the effectiveness of air filters, they only deal with particulate matter, whereas indoor air pollution includes chemical vapors. In this situation, biofilters such as iVGS may be effective in filtering out VOCs.

Indoor thermal comfort depends on air velocity. A room of constant temperature and devoid of air movement is perceived as uncomfortable and stifling, whereas high air velocities cause discomfort and a sensation of coldness (Liu et al., 2017). High air velocities in buildings can be reduced using green infrastructure (Jaafar et al., 2013; Perini et al., 2011), as well as by using façade treatments. To achieve indoor thermal comfort, the temperature is suggested to be between 19 and 28°C (ASHRAE, 2020). Warmer temperatures may induce unwanted gaseous emissions from furniture, since chemicals are more volatile at higher temperatures. For example, it has been found that even at 23°C, certain types of flooring emit small quantities of VOCs (Wiglusz et al., 2002). Thermal comfort levels also depend on relative humidity. Warm temperatures and high humidity promote odour (Fang et al., 1998), which can produce an unacceptable indoor environment.

Sound has different levels and a number of categories. High noise levels can affect people physically and physiologically, affecting their hearing and increasing blood pressure and stress (Liu et al., 2017). Establishing limits and providing guidelines may assist in providing comfortable levels, but noise from the outdoor environment is beyond the building occupants' control and therefore additional measure are often needed. Urban background noise such as railways and automobile traffic can be troublesome and affect productivity (Al horr et al., 2016). Manipulating the characteristics of the geometry of the urban environment and surface acoustic features by using noise propagation calculations can provide information on the potential impact of intervention solutions (Magrini & Lisot, 2015). Limiting noise into the interior environment can also be done using double skin façade (Lee & Chang, 2015). For indoor finishing, the use of materials such as rice husk mixed with cement binder and sand as wall surface material has been found to be suitable to be applied as sound reducer, as compared to coconut coir fiber and sawdust mixture (Tengku Izhar et al., 2014). Other methods to reduce indoor noise can be achieved by using furniture (Chen et al., 2018), the use of ceiling tiles to absorb noise, and ensuring a good space layout (Al horr et al., 2016).

Visual quality or comfort also has an impact in establishing an acceptable interior environment. Certain shapes can play a role in providing visual comfort: curvilinear forms on interior furniture and finishes elicit feelings of calm, happiness, and relaxation (Dazkir & Read, 2012). Visual comfort is also affected by lighting. Harsh lighting can cause occupants to experience tiredness, stress, or headaches (Kuller, 1986). Visual lines of sight through windows are important as they provide views outside as well as letting in daylight. Letting in daylight has been shown to improve psychological well-being (Hwang & Jeong, 2011). Windows with views of greenery have been found to increase performance as well as reduce stress and mental fatigue (Bratman et al., 2012; Li & Sullivan, 2016; Nagy et al., 1995; Tennessen & Cimprich, 1995). On the contrary, rooms with no windows negatively affect production of hormones such as cortisol (Kuller, 1986). However, windows can be a major source of unwanted heat gain (or loss) and therefore affect thermal comfort (Menzies & Wherrett, 2005), and increase energy use.

Green Buildings

The goal of a green construction is to use resources more efficiently. Green building practice aims to ensure minimal negative environmental impacts during and after construction, ensuring the well-being of the building occupants and provide environmental and economic benefits (Hussain et al., 2014; Zuo & Zhao, 2014). The reasons for establishing green building rating systems revolve not only around improved economics but also issues of social equity and as a countermeasure to the side effects of development. According to the Green Building Council in the United Kingdom, green buildings are meant to enhance the sustainability of the built environment (Ade & Rehm, 2020), while the United States Green Building Council aims for green buildings to have minimal (or nil) negative impacts on the occupants and the environment (Abbaszadeh et al., 2006).

There are various green building certification systems used worldwide and others developed specifically for certain countries. The world's first green building rating tool was developed in the 1990s and was known as the Building Research Establishment Environmental Assessment Method (BREEAM), which assessed the environmental performance of a building. Later, in 1998, LEED 1.0 was developed and LEED v4.1 has now gone through several improvements.

Some of the benefits of meeting a green building standard include reduced carbon emissions, increased property values, lower operating costs, and improved indoor environmental quality (Ade & Rehm, 2020). An example of a new building that achieved a six-star rating by Green Star is the Frank Fenner Building at the Australian National University (Figure 1). The building was the first in the Australian Capital Territory to receive a six-star award. Six key features that contribute to its six-star green rating are its rooftop photovoltaic solar panels, water recycling, solar orientation, efficient thermal exterior, airflow and ventilation, and minimal out-gassing of the interior (Australian National University, n.d.).

Previous studies have come to mixed conclusions regarding the effectiveness of green buildings. Comparisons (pre- and post-occupancy) between three green buildings in South Africa found significant improvements in perceived air quality, self-reported productivity, and physical well-being. However, there was no significant difference in psychological well-being, job satisfaction, propensity to leave the organisation, or organisational image (Andrew & Karen, 2016). Some studies have found higher IAQ ratings in green buildings, while others have found the opposite; a number have seen no difference (Steinemann et al., 2017). One building in Korea received the highest ranking from Korea's Green Building Council, but feedback from the workers revealed the visual environment and indoor lighting quality were poor (Hwang & Jeong, 2011). A rising concern in the green building movement is greenwashing, where the so-called 'green' building materials are not actually green. Greenwashing is the act of portraying widely accepted or supposedly environmentally harmful practices in a positive light (Spiegel & Meadows, 2010). Therefore, it is important to understand the true meaning of green design, while noting any additional measures that may be needed to tackle local environmental issues. In the end, we need to understand how the most sustainable materials and practices can be selected so as to ensure that a 'green' building really is green.

Conventional buildings can also be renovated and retrofitted to achieve the green building status. The next section discusses how green infrastructure can be used as a tool to aid in qualifying the green building certification.

Figure 1: Frank Fenner Building, Fenner School of Environment and Society, ANU, showing views of solar panels on roof and the water recycling system (Australian National University, n.d.).

Retrofitting Green Infrastructure to Achieve Green Building Certification

Retrofitting, which is the process of incorporating new features or technologies into an existing structure, is frequently done to increase safety and comfort levels. In general, a green retrofit upgrades a building so as to achieve improvements in energy use and environmental performance, reduce waste, improve indoor environmental conditions, and bring financial benefits to the building's owner. A challenge of green retrofits is ensuring that these benefits are sustainable in the long term. Green buildings use sustainable materials that are designed to be environmentally friendly. Nevertheless, such materials can sometimes emit pollutants, such as ozone, because of their bio-based ingredients (Hoang et al., 2009).

Upgrading and retrofitting green technologies in conventional buildings, guided by a green building rating system, can improve a building and make it more sustainable. There are examples of conventional buildings that have successfully achieved green building status, such as the new *Pertubuhan Arkitek Malaysia* Centre in Malaysia where they purchased an old building and implemented a green approach when renovating the building into a certified green building. Other similar projects include the Empire State Building in New York, which received LEED Gold for Existing Buildings certification in September 2011, and the Wollongong City Council Administration Building, Australia, which received a six-star Green Star Rating in 2019. The addition of green infrastructure contributed to green certification for both of these buildings.

Of late, studies on the impact of retrofitting green infrastructures are gaining attention due to the longer time people are spending indoors; often people are unable to go outside or due to certain restrictions (Chan et al., 2021; Yin et al., 2020). Retrofitting of buildings can improve their overall condition, thus providing an improved interior environment for their occupants. The use of green infrastructures such as VGS and iVGS has potential to contribute to green building retrofits because it can potentially affect several of the criteria that green building certification seeks to address, especially related to IEQ. In the next section, we explore and identify the benefits that VGS or iVGS can bring in terms of producing a more acceptable IEQ, one aligned with the objectives of green building certification ratings.

The Potential of VGS for Retrofitting Buildings for Green Certification—A Case Study

This study compares LEED, Green Star, and GBI assessment criteria, specifically regarding IEQ.

- **LEED** is the world's most frequently utilised green building grading system with goals to create buildings that enhance human health, protect water resources, lessen the impact on climate change, protect biodiversity and the ecosystem, encourage the use of regenerative and sustainable materials, and boost the quality of life.
- **Green Star** is developed by Green Building Council of Australia (GBCA), for the Australian environment. Representatives from numerous organisations contributed to and helped establish the Green Star rating system and the rating tools, with objectives to reduce the impact of climate change, to enhance health and quality of life, promote resilience in communities and buildings, assist in market transformation and a sustainable economy, and finally to protect and restore the ecosystem and biodiversity.
- **GBI** is a nationally recognised green grading system for buildings in Malaysia. Its purpose is to encourage sustainability in the built environment and to increase public and professional knowledge of environmental challenges and our duty to future generations. The GBI rating tool gives developers and building owners the chance to plan and build environmentally friendly, sustainable buildings that can save money on energy and water, create healthier indoor environments, have better access to public transportation, and incorporate recycling and landscaping into their projects to lessen their impact on the environment.

There are similarities in the rating criteria listed in LEED, Green Star, and GBI. As shown in Table 1, materials, water efficiency, energy, IEQ, and innovation are included as assessment criteria by all certification bodies. In the assessments, the materials criteria mean that points can be earned by using sustainable materials, reducing waste, and recycling, as well as the use of green products. Water efficiency criteria outline minimal use of potable water by reusing resources such as rainwater, as well as minimizing the needs for water inside the building. In terms of energy criteria, a green building must be energy efficient and of high performance. Innovation in green building design is welcomed by all three certification bodies. For IEQ criteria, points are given to buildings with acceptable IAQ, lighting comfort, daylight, views, mould prevention, internal noise levels, and thermal comfort. The remaining assessment criteria are location, transport, resources, atmosphere, sustainable site, regional priority credits, management, land use, ecology, and finally emissions.

Table 1
Criteria included in three green building certification schemes: LEED v4 for Building Design and Construction [updated 25 July 2019]; Green Star Rating—Design & As Built; and GBI assessment criteria.

Green building certification assessment criteria	LEED	Green Star	GBI
Location	✓		
Transport	✓	✓	
Materials	✓	✓	✓
Resources	✓		✓
Water efficiency	✓	✓	✓
Energy	✓	✓	✓
Atmosphere	✓		
Sustainable sites	✓		✓
Indoor environmental quality	✓	✓	✓
Innovation	✓	✓	✓
Regional priority credits	✓		
Management		✓	✓
Land use and ecology		✓	
Emissions		✓	

As mentioned earlier, the quality of the interior environment is commonly affected by its IAQ. For the purpose of green building certification, it is quantified by thresholds (+1 point where human health is at risk) or by occupant satisfaction and productivity (Spiegel & Meadows, 2010). For green buildings, the air quality assessment criteria are monitoring, control, and prevention of air pollutants, as well as identifying pollutant sources. Table 2 displays the list of IEQ points used by the LEED, GBI, and Green Star Rating. There are some similarities and differences in the IEQ ratings between these certification bodies. Most of the criteria are achievable via the correct choice of indoor finish and materials, as well as by mechanical means of managing the IEQ. The three guidelines consistently indicate that lighting, acoustics, IAQ, thermal performance, and views are important criteria to achieve IEQ points.

The importance of achieving an acceptable IEQ is reflected by findings that IEQ reduces absenteeism and improves productivity (Singh et al., 2010). Data shows that green buildings positively benefit water and energy conservation, although there is not so much an effect on health and IEQ (Allen et al., 2015) since most green building credits relate to environmental sustainability, which is easier to achieve (Andrew & Karen, 2016). An increase focus on achieving environmental sustainability is needed as elevated risk to the health of the building occupants such as stress and mental health are becoming increasingly common in urban workplaces (Evans, 2003; Lottrup et al., 2013; Velarde et al., 2007).

Table 2
Similarities and differences in IEQ ratings between three green building assessments: LEED v4 for Building Design and Construction [updated 25 July 2019], GBI Assessment Criteria, and Green Star Rating—Design & As Built.

IEQ Assessment Criteria	IEQ Points		
	LEED	GBI	Green Star
Carbon dioxide monitoring and control		✓	
Environmental tobacco smoke	✓	✓	
Indoor air pollutants		✓	
Internal noise levels/acoustic comfort and performance	✓	✓	✓
Increased ventilation/air exchange		✓	
Mould prevention		✓	
Thermal comfort	✓	✓	✓
Visual comfort/quality views/external views	✓	✓	
Construction IAQ management plan	✓		
Enhanced indoor air strategies	✓		
IAQ assessment	✓	✓	
Hazardous materials			✓
Low-emitting materials	✓		
Occupant comfort survey		✓	✓
Daylight and views/daylight glare and views	✓	✓	✓
Interior lighting/electric lighting levels/lighting comfort	✓	✓	✓
Minimum IAQ performance/quality of indoor air	✓	✓	✓

The use of vertical greenery carries many benefits that can aid in green building certification process (see Table 3). Both iVGSs and VGSs has been found to affect temperature, energy use, sound quality, and air quality—items that are closely related to the IEQ points listed in green building requirements (Ghazalli et al., 2019). The flexibility of VGS installation is also considered as one of the many benefits of VGS. Generally, the difference between an outdoor and indoor VGS is the planting system, media, plant selection, and maintenance routine. The planting systems are generally divided into three types: modular, indirect greening (e.g., using a mesh structure), and direct greening (plants directly on walls). The modular planting system is more suitable for indoor locations as it is flexible and easier to maintain. If certain plants need to be replaced, the specific plant or module can be removed, generally without affecting the rest of the system. Planting systems using planter boxes or a trellis are more suitable outdoors, where there is a broader plant selection. The inclusion of plants in VGS is the main contributing factor in providing beneficial sustainable and ecosystem services to the indoor environment.

Table 3
Key contribution of iVGS or VGS to indoor environmental quality (IEQ) points for green building certification.

Assessment Criteria	**Cause of improvement**	**Key contributions to IEQ Points**
CO_2 monitoring and control	iVGS	Absorbs CO_2 (Poórová et al., 2020; Torpy et al., 2017; Yarn et al., 2013).
Environmental tobacco smoke	iVGS	Acts as particulate sink (Torpy et al., 2018).
Indoor air pollutants	iVGS	Removes VOC (Torpy et al., 2018).
Mould prevention	Plants	Effectively remove mould (Garg et al., 2021).
	Mechanical means	Ventilation system to regulate air, humidity levels, and temperature or use of anti-microbial coating where necessary.
Increased ventilation/air exchange	VGS	Vertical greenery's purifying capabilities is the combination of plants (Wei et al., 2021) and the substrate (Pettit et al., 2018), aligned with the objectives of air exchange. VGS affects ventilation into the building (Sunakorn & Yimprayoon, 2011).
Minimum IAQ performance	Mechanical means	The use of mechanical ventilation systems with ventilation rate procedures defined by ASHRAE.
Construction IAQ management plan	Managerial	The plan to protect well-being of workers during the construction stage and when occupants are moving in.
Enhanced indoor air strategies	iVGS	As plants are known to trap dust, the use of iVGS makes a beneficial contribution (Panyametheekul et al., 2016; Perini et al., 2017).
	Managerial	It is recommended to install permanent entry-way systems with mats to capture dirt and dust.
IAQ assessment	Managerial	Identifying maximum allowed concentration for selected indoor air contaminant, as well as methods to test them.
Hazardous materials	Managerial	Identifying location of hazardous materials when present and guidelines on how to remove them.
Low-emitting materials	iVGS	Lifecycle studies provides information on how iVGS can be installed using sustainable materials that do not emit additional volatile pollutants (Manso et al., 2018).
	Managerial	Seeks to establish minimal indoor contaminant exposure by choosing materials that specifies emission evaluation.
Internal noise levels/acoustic	iVGS	Studies show iVGS to be efficient in achieving desirable acoustic comfort (Azkorra et al., 2015; Fernández-Bregón et al., 2012; Guillaume et al.,

comfort and performance		2015; Horoshenkov et al., 2011; Ismail, 2013; Shimizu et al., 2016; Wong et al., 2010).
	Mechanical means	Vertical shading devices can be used as an aid for sound transmission, as shown in a study by (J. Lee & Chang, 2015) where thicker shading devices improved sound transmission loss.
Thermal comfort	iVGS	Reduces indoor temperature (Fernández-Bregón et al., 2012; Fernández-Cañero et al., 2012; Pérez-Urrestarazu et al., 2016; Poórová et al., 2020).
Visual comfort/quality views/external views	iVGS	iVGS creates visual interest (Ghazalli et al., 2018).
	Indoor plants	Indoor plants are valuable additions as they increase productivity, improve mood, and improve health (Adachi et al., 2000; Bringslimark et al., 2011; Fjeld et al., 1998; Han, 2008; Park & Mattson, 2009; Shibata & Suzuki, 2004).
Daylight and views/daylight glare and views	iVGS	Plants within a double skin façade (typically climber system of vertical greenery) provide shade and block solar radiation (W. Fang et al., 2011).
	Mechanical means	Glare control using blinds, tints, or the use of cladding. Outside views must be preserved with 40% or more visible light transmittance.
Interior lighting/electric lighting levels/lighting comfort	Mechanical means	Green Star awards points for buildings that measure, monitor, and manage lighting levels. Appropriate lighting levels are important as different spaces require different amounts of light. Strategies include light control using dimmable lights and surface reflectivity.
Occupant comfort survey	Managerial	The survey intends to understand users' or occupants' satisfaction with the environmental quality of the building. The survey will further verify if all the measures taken to achieve the green building status are able to provide comfort as well as optimal conditions that foster well-being.

All three green building assessments used in this study award points for life cycle assessment (LCA), to show that their project performs better in most impact categories. LCA considers the entire life cycle and prohibits burden shifting, it stops environmental impact from being reduced at one stage of the life cycle while growing at subsequent stages. Energy analyses demonstrated the VGS used in retrofit projects is completely sustainable (Pulselli et al., 2014). However, the success is governed by the materials and planting system. Pre-installation phase material selection has the biggest impact on the overall life cycle burden (Natarajan et al., 2014). LCA studies shows that a VGS can be selected to give minimal environmental burden if it uses industrial waste (mud) and natural materials (expanded black cork board and expanded black cork granules) (Manso et al., 2018). For planting systems, a study by (Huang et al., 2019, 2021) found that VGS using indirect greening system has the lowest life-cycle cost while modular systems have the highest life-cycle cost. Indirect system (planting system using trellis) has lower life-cycle cost because of its simpler structure, reduced plant utilisation, and lower rate of plant replacement. In comparison to indirect and modular systems, LCA findings showed that VGS using felt-layer systems are less environmentally friendly in terms of air cleansing and energy savings (Ottelé et al., 2011). These findings emphasise the importance of careful planning and decision-making when choosing VGS that are appropriate for the built environment, especially in acquiring green building certification. In areas where there is limited ground available for landscaping or gardening, VGS on building walls helps conserve energy for cooling, and is an environmentally viable choice.

Air Quality

In providing acceptable IEQ, green building assessments outline several strategies and the use of VGS adds value in several potential assessment criteria such as improving air quality. Providing acceptable IAQ for building occupants requires several strategies: carbon dioxide (CO_2) monitoring and control, environmental tobacco smoke, indoor air pollutants, mould prevention, increased ventilation/air exchange, minimum IAQ performance, construction IAQ management plan, enhanced indoor air strategies, and IAQ assessment (see Table 3). For CO_2 monitoring and control, plants on a VGS use CO_2 to produce oxygen (O_2), which in return benefits building users (Poórová et al., 2020; Torpy et al., 2017; Yarn et al., 2013). Studies using iVGS also show that, among other benefits, they remove VOCs (Torpy et al., 2018). High air pollution levels are not entirely due to poor choice of materials or bad maintenance practices. Pollutant sources can include outdoor air, human activity, and cleaning products (Raji et al., 2015). Further, these emissions are influenced by temperature and humidity. For example, environmental tobacco smoke is one of the primary sources of particulate pollution (in areas where smoking has not been restricted or banned) and can be managed by minimising indoor exposure (Stevulova, 2012) as well as using VGS as particulate sink (Pettit et al., 2019). In areas where there is little ventilation, plants on iVGSs adsorb particulate pollutants gravimetrically (Ghazalli et al., 2018).

Another issue regarding air quality is the presence of mould. The use of iVGS can assist in mould control as the presence of indoor plants can lessen airborne mould (Garg et al., 2021). The development of mould is a source of gaseous pollutants but it can be prevented by controlling the humidity levels indoors.

Ventilation in building design is important for humidity control as well as helping with air quality, stopping condensation, and regulating temperature. It is advisable that fresh outside air is introduced inside buildings every 4 hours to help dilute indoor air that might be polluted. A study comparing rooms with and without a bio-façade concluded that the room with the bio-façade had higher air velocity, indicating that the VGS affected ventilation (Sunakorn & Yimprayoon, 2011). Air velocity is affected by temperature changes, and findings on the way VGS changes indoor temperature may explain the change in air velocity. Due to the purifying capabilities of plants and the natural process of photosynthesis that produces oxygen, the use of iVGS may assist in ensuring fresh air supply indoors (Wei et al., 2021). For plants on iVGS, airflow through the plants and their large surface area increases the purifying capabilities (Pettit et al., 2018). It is also important to monitor humidity so as not to exceed the recommended levels. According to LEED monitoring humidity ensures comfort and lessen the chance of mould growing, while GBI listed humidity as part of IAQ parameters. Humidity monitoring is achievable via mechanical aspects of buildings.

The IEQ assessment criteria pertaining to air quality includes a wide range of categories: from CO_2 monitoring, to increased ventilation/air exchange, to low-emitting materials, to minimum air quality performance (Table 3). Some of these criteria can be fulfilled, at least in part, by green infrastructure and by integration with managerial and mechanical means. Enhanced indoor air quality strategies, for example, recommend installation of permanent entry-way systems with mats to capture dirt and dust. As plants are known to trap dust, the use of iVGS around these entry-ways can provide an additional or complementary beneficial contribution (Panyametheekul et al., 2016; Perini et al., 2017). The criterion seeks to establish minimal indoor contaminant exposure by choosing suitable materials. For instance, laminated floorings emit harmful VOCs, especially at higher temperatures (Wiglusz et al., 2002) and their use is discouraged. In this way, iVGS may contribute to removing pollutants without their supporting structures themselves emitting volatile pollutants indoors.

Acoustic/noise

Indoor noise is generally generated by people and building systems. It is important to maintain an acceptably quiet environment as prolonged exposure to loud noise causes hearing problems and can affect performance as well as productivity (Abdulaali et al., 2020). Thus, in the same way as air quality and thermal comfort is important to green building requirements, so too is acoustic comfort. Such noise limitation is also emphasized by all three certification bodies used in this study (Table 2). However, in terms of acoustic performance, studies have shown that green buildings have similar or less satisfactory levels than conventional buildings (Abbaszadeh et al., 2006; Paul & Taylor, 2008; Rao et al., 2012). Vertical shading devices can be used as an aid for sound transmission, where thicker shading devices improved sound transmission losses (Lee & Chang, 2015). A VGS can also be an effective noise filter (Azkorra et al., 2015; Ismail, 2013; Shimizu et al., 2016) because research indicates that plants can effectively absorb sound (Horoshenkov et al., 2011). One indoor experiment indicated that an iVGS was able to mitigate noise, with noise mitigation from a wall with an iVGS between 2% and 8% lower than walls without an iVGS (Fernández-Bregón et al., 2012), and it does not necessarily have to employ an abundance of plants (Pérez et al., 2016). However, the effectiveness of iVGSs in noise filtering is influenced by the planting system (Wong et al., 2010) and the location on the building (Guillaume et al., 2015; van Renterghem et al., 2013). A study showed VGS using modular system (removable pots with 0.28 m substrate) has the best insertion loss or noise reduction level (Wong et al., 2010) and substantial effect can be seen if the VGS is installed in the top section and outside the street (depending on the placement of VGS, frequency bands, and quantity of reflections on the treated materials) (Guillaume et al., 2015).

Thermal Comfort

Most studies on vertical greenery focus on how it affects temperature, regardless of whether the VGS is indoors (Fernández-Bregón et al., 2012; Fernández-Cañero et al., 2012) or outdoors (Cuce, 2017; Fang et al., 2011; Sunakorn & Yimprayoon, 2011). Both iVGS and VGS can influence indoor temperature levels. A VGS installation reduces building surface temperatures and therefore helps reduce and stabilize indoor temperatures, as well as enhancing thermal insulation, and can also be used as an effective passive system for saving energy (Cuce, 2017; Manso & Castro-Gomes, 2015; Vox et al., 2017; Wong et al., 2009;

Yoshimi & Hasim, 2011). Studies on the thermal performance of iVGS have also shown they are beneficial in reducing elevated indoor temperatures (Fernández-Bregón et al., 2012; Poórová et al., 2020) as well as humidity (Pérez-Urrestarazu et al., 2016). Reviews on the link between VGS and temperature have cited 10 or more studies, showing that much work has been done to understand this relationship (Charoenkit & Yiemwattana, 2016; Hunter et al., 2014). These findings generally show that vertical greenery can help achieve desirable indoor thermal levels. Other than the use of VGS, thermal comfort can also be achieved using shading devices installed on the building façade. Efficiency relies on the orientation of the shading device, and proper study is needed before installation (Lee & Chang, 2015).

Visual Comfort

The mechanical aspect of the assessment criteria involves technical aspects of the building construction, and here the IEQ criteria includes daylight, lighting, daylight glare and views.

Daylight and views are important, as highlighted in Green Star ratings, since they help prevent fatigue. The visual environment is important for people who spend many hours indoors. In LEED, quality of views refers to adequate outside views to promote connection with the natural environment. Windows are more appealing in offices, and it is suggested that the use of underground office space should be avoided (Nagy et al., 1995). Studies comparing views with and without elements of nature have found that views of nature are preferable, and have a positive effect on mood and concentration (Lee et al., 2015; Tennessen & Cimprich, 1995; van den Berg et al., 2003). The presence of nature, even via an artificial window system, has benefits for viewers (Radikovic et al., 2005). Here, the use of iVGS is suggested to be beneficial in providing quality views in areas with no natural views. All three certification bodies (LEED, GBI, and Green Star) does not credit the value of iVGS or any other type of greenery views in the absence of windows. Perception studies report that the use of a VGS enhances visual quality, reduces stress (Abdul-Rahman et al., 2014), and is considered aesthetically pleasing and restorative (White & Gatersleben, 2011). The visual comfort offered by VGSs occurs through aesthetic enhancement and bringing nature closer to the building occupants.

For daylight glare and views, VGS/iVGS offers an organic solution. Typically blinds, tints, or the use of cladding help control glare. However, according to LEED, outside views should be preserved, with 40% or more visible light transmittance. In glare control, the use of plants within a double skin façade (Façades with two layers typically made of glass that have an intermediate cavity through which air can pass. This area insulates the building from harsh winds, noise, and temperatures, increasing its thermal efficiency) has been shown to provide shade and blockage of solar radiation (Fang et al., 2011), bringing psychological comfort to building occupants (Larsen et al., 2014) .

In the 1970s, green building rating tools were shaped by efficient energy measures. Studies concluded that VGS could support improved energy efficiency and those benefits could be incorporated in the tools. More recently though, the rating tools have shifted focus until currently they focus more on promoting health and fighting disease (Licina et al., 2021). Studies on vertical greenery research demonstrate strong health and community benefits, as well as sustainability of urban areas such as: environmental, health and community, financial, and industry benefits (Ling & Chiang, 2018). Retrofitting conventional buildings can improve IEQ (Breysse et al., 2011), and iVGS studies have found positive reactions (van den Berg et al., 2017). It is important then that the benefits VGS and iVGS bring is acknowledged and can be incorporated into green building certification requirements (Table 3).

Limitations

Findings presented in this study shows VGS/iVGS can positively influence IEQ requirements of green building certification: air quality, acoustic or sound quality, thermal comfort, and visual comfort. However, there are several criteria that are predominately fulfilled only through mechanical means and managerial process. In Table 3, these assessment criteria—construction IAQ management plan, enhanced indoor air strategies, IAQ assessment, hazardous materials, low-emitting materials, post-occupancy comfort survey—are listed under managerial aspects. A construction IAQ management plan involves planning during the construction phase to ensure that the comfort and well-being of workers is met, as well as planning to prepare the building for occupants to move in. In LEED, the IAQ assessment criteria specify the maximum allowed concentration of selected indoor air contaminants, as well as methods to test them. For example, the maximum concentration for formaldehyde is 27 ppb and 50 $\mu g/m^3$ for PM_{10}. Hazardous materials such as lead and polychlorinated biphenyls are commonly found in older buildings. According to Green Star IEQ requirements, points are given for identifying the location of hazardous materials (if any) and their removal during renovation.

According to all three assessment bodies, interior lighting and the quality of the indoor air are both given important weightings, and both are included as mechanical measures in the green building assessment criteria (Table 3). The purpose of good interior lighting is to aid comfort, well-being, and productivity. Green Star awards points for buildings that measure, monitor, and manage lighting levels. Appropriate lighting levels are important as different spaces require different amounts of light. Potential strategies include light control using dimmable lights and surface reflectivity. Establishing a minimum IAQ performance involves adhering to the minimal requirements for ventilation, guided by organizations such as ASHRAE.

Finally, to review the impact of IEQ requirements on building occupants, a survey should be made. The survey is intended to understand users' or occupants' satisfaction with the environmental quality of the building. The survey will verify if all the measures taken to achieve the green building status provide comfort as well as optimal conditions that foster well-being. However, findings on the health impact of green buildings in a real-world setting are limited (Licina et al., 2021). IEQ variables such as thermal comfort and ventilation have been found to be less than satisfactory (Ravindu et al., 2015). The guidelines provided may or may not work in a given locations. Although in the assessment points are provided for innovation, more are given for sustainable practices. It should include a flexible and climate-responsive design approach suited to the specific site.

Figure 3: DPR Construction’s Phoenix Regional Center, Arizona (image from DPR Construction Phoenix Regional Office | WBDG - Whole Building Design Guide, n.d.)

As shown in Table 2, there are similarities and differences in IEQ ratings between LEED, GBI, and Green Star. These tools do not all measure the same thing except for criteria associated with acoustic, thermal, daylight, views, lighting, and minimum IAQ performance (Table 3). Green Star and LEED is more likely to identify and credit the use of vertical greenery, as shown by several completed accredited projects. For example, the DPR Construction’s Phoenix Regional Center, Arizona (Figure 2) which earned a Platinum LEED rating and a certification for using zero energy (*DPR Construction Phoenix Regional Office | WBDG - Whole Building Design Guide*, n.d.), and Council House 2 in Melbourne (Figure 3) that became the first to receive Six Green Stars (*CH2 Melbourne City Council House 2 / DesignInc | ArchDaily*, n.d.). However, there is no mention specifically on the use of vertical greenery in achieving points for green building certification. The Forestry Building of Fenner School of Environment and Society, Australian National University (ANU) were scored before the installation of iVGS, and this raises the question would any of the tools give a significantly improved score or just stay the same. Looking at LEED’s rating, it measures the “atmosphere” while the others do not – given this study presents input on how small iVGS changed the “atmosphere” in the Forestry Building corridor, LEED might reward the installation, while the others did not.

Figure 3: Council House 2, Melbourne (image from CH2 Melbourne City Council House 2 / DesignInc | ArchDaily, n.d.)

Conclusion

Vertical greenery has been demonstrated to have positive effects on several criteria related to improving green building scores. iVGS/VGS can be feasibly retrofitted to buildings without taking up valuable floor space. This study has summarised the opportunities (as guided by the IEQ ratings for green building assessment listed in LEED, GBI, and Green Star) to retrofit VGS, especially iVGS, into conventional buildings so as to increase IEQ and improve the health of building occupants. This study has also presented findings on the benefits of installing iVGS (and VGS), and how this can add to the IEQ rating and assist in attaining green building certification. The use of iVGS offers the benefits of greenery, while saving space because of its vertical placement.

Given the positive relationship between nature, IEQ, and well-being, we conclude that iVGSs provide noteworthy contributions to strengthening a green building's IEQ requirements. Previous work on green building research has concluded that the social and psychological aspects are not well addressed in the rating tools (Andrew & Karen, 2016; MacNaughton et al., 2017; Zuo & Zhao, 2014). iVGS has been shown to improve occupants' psychological states and assist in creating a healthier and more comfortable environment.

Thus, retrofitting iVGSs into a conventional building may improve the cognitive functioning of the occupants. Cognitive function is important as it not only involves problem solving, but also learning, memory, decision making, and attention. Visual comfort is important for individuals working for long periods and the calming effect of plants can provide positive outcomes in terms of psychological well-being.

The numerous benefits of iVGSs and VGSs presented in this study indicate that these systems align with green building objectives. These systems provide environmental, health and community, financial, and industry benefits. The benefits outlined in this study support the use of VGS as a green retrofit and help achieve green building certification requirements, however the rating tools needs to be updated to incorporate VGS as components of green building. Given the known benefits of greenery for human health, it can be concluded that the use of a VGS provides more than just environmental quality points. VGS contributes greatly to reducing stress and enhancing the mental well-being of the building occupants, and this is a criterion not conventionally measured when aiming for green building status.

Funding
This study was funded by Malaysia Ministry of Education and Universiti Putra Malaysia.

Disclosure Statement
The authors report no potential conflict of interest.

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