Paper submitted to the *Shanxi (Taiyuan)-Hong Kong Joint Symposium 2017*, Smart City – The way to a better tomorrow, 30 Jun-1 Jul 2017, Taiyuan, Shanxi Province, China. 晉港建築設備工程技術交流會, 山西省太原市

Assessment of environmental performance of vertical greening systems

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Abstract

Vertical greening systems are also known as green walls, living walls, or green facades. They are considered a sustainable/green building design approach and are becoming increasingly popular in the world. By using the natural processes of the vegetation, they can contribute to mitigating urban heat island, enhancing building's thermal performance, saving cooling energy and improving air quality. As the space available for greening is often very limited in urban cities, vertical greening can be an effective method to improve the city environment.

However, as vertical greening systems require materials to build and resources to maintain, there are queries about whether they are really worthy for adoption and how to enhance their environmental performance. This research aims to assess the environmental performance of vertical greening systems and investigate the important considerations for effective and sustainable building design. The common types of vertical greening systems are evaluated and the key factors of environmental performance are examined. To enhance the environmental performance and potential benefits of the vertical greening, the life cycle environmental impacts, integrated sustainable technologies and holistic ecological and social factors should be considered carefully in the planning, design and maintenance of the systems.
(193 words)

Keywords: Vertical greening systems, environmental performance, urban cities, Hong Kong.

垂直綠化系統之環境績效評估

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摘要:
垂直綠化系統也被稱為綠色牆，活生牆或綠色外牆。 它們被認為是可持續/綠色的建築設計方法，並且在世界上越來越受歡迎。 通過使用植被的自然過程，它可以有助於減輕城市熱島，提高建築的散熱性能，節約空調能源和改善空氣質量。 由於城市可綠化面積常常很有限，因此垂直綠化是改善城市環境的有效手段。 然而，由於垂直綠化系統需要許多資源建立和維護，因此關於它們是否真正值得採用以及如何提高其環境績效一直存在疑問。本研究旨在評估垂直綠化系統的環境績效，並研究有效和可持續建築設計的重要考慮因素。對常見的垂直綠化系統進行了評估，並對環境績效的關鍵因素進行了考察。為了提高垂直綠化的環境績效和潛在效益，在系統的規劃，設計和維護中，應仔細考慮生命週期環境影響，綜合可持續技術以及整體生態和社會因素。

關鍵詞: 垂直綠化系統，環境績效評估，都市，香港。

1. INTRODUCTION

Rapid development of urban cities is causing much environmental and ecological concerns. For smart and sustainable cities, in order to achieve smart environment, it is necessary to apply new urban greening concepts. Vertical greening systems (VGS) can be defined as structures that allow vegetation to spread over a building facade or interior wall (Pérez-Urrestarazu, *et al.*, 2016). They are also known as green walls, living walls, or green facades. VGS are considered a sustainable/green building design approach (Perini, *et al.*, 2011; Sheweka and Mohamed, 2012) and are becoming increasingly popular in the urban landscapes in China and in the world (Ma, *et al.*, 2013; Perini, *et al.*, 2013). By using the natural processes of the vegetation, they can contribute to mitigating urban heat island, enhancing building's thermal performance, saving cooling energy and improving air quality. As the space available for greening is often very limited in urban cities, vertical greening can be an effective method applied to the exterior and interior surfaces of buildings to improve the city environment. Figure 1 shows two examples of vertical greening for outdoor and indoor applications, respectively.

(a) Outdoor green wall (Taichung, Taiwan)

(b) Indoor green wall (International Commerce Centre, Hong Kong)

Figure 1. Examples of vertical greening for outdoor and indoor surfaces

In fact, vertical greening is not a new concept and many people refer its historical origin to the traditional greening methods of Hanging Gardens of Babylon and other ancient empires (GRHC, 2008; Manso and Castro-Gomes, 2015). The modern forms and techniques of VGS were developed and proliferated in Europe, with France and Germany being the important pioneers (Brandwein, 1987; Köhler, 2008; Weinmaster, 2009). At present, VGS are related to many descriptive terms such as green walls, living walls, living cladding, green facades, green screens, vertical green, vertical gardens, vegetated wall surfaces, bio-walls, bio-facades and bio-shades. In mainland China, "three-dimensional greening" is often used which refers to combination of building wall, roof, balcony, window and other special space with greening design (Cui and Zheng, 2016). In terms of spaces and functions, there are four common types of VGS applications:

- Building facades or outdoor vertical surfaces
- Interior walls or indoor vertical surfaces
- Noise barriers (such as along the roads), site hoarding boards, and free-standing structures
- Slopes and retaining walls

Nowadays, VGS are at the cutting edge of architectural and interior design trends (Weinmaster, 2009). They are also applied as a sustainable strategy of urban rehabilitation and building retrofitting (Peng, 2013). However, as VGS require materials to build and resources to maintain, there are queries about whether they are really worthy for adoption and how to enhance their environmental performance. Honan (2015) has prepared a critical green wall sustainability analysis and questioned the validity of the vertical gardens installed at One Central Park Sydney. Ottelé, *et al.* (2011) pointed out that it is eventually not clear if green wall systems are sustainable, due to the materials used, maintenance, nutrients and water needed. Thus, it is essential to evaluate the environmental performance of VGS and ensure the potential benefits can be realised and maximised.

This research aims to assess the environmental performance of VGS and investigate the important considerations for effective and sustainable building design. The common types of VGS are evaluated and the key factors of environmental performance are examined. It is hoped that useful information can be generated to help people determine the strategy for planning, designing and maintaining VGS that are environmentally and ecologically sound.

2. VERTICAL GREENING SYSTEMS

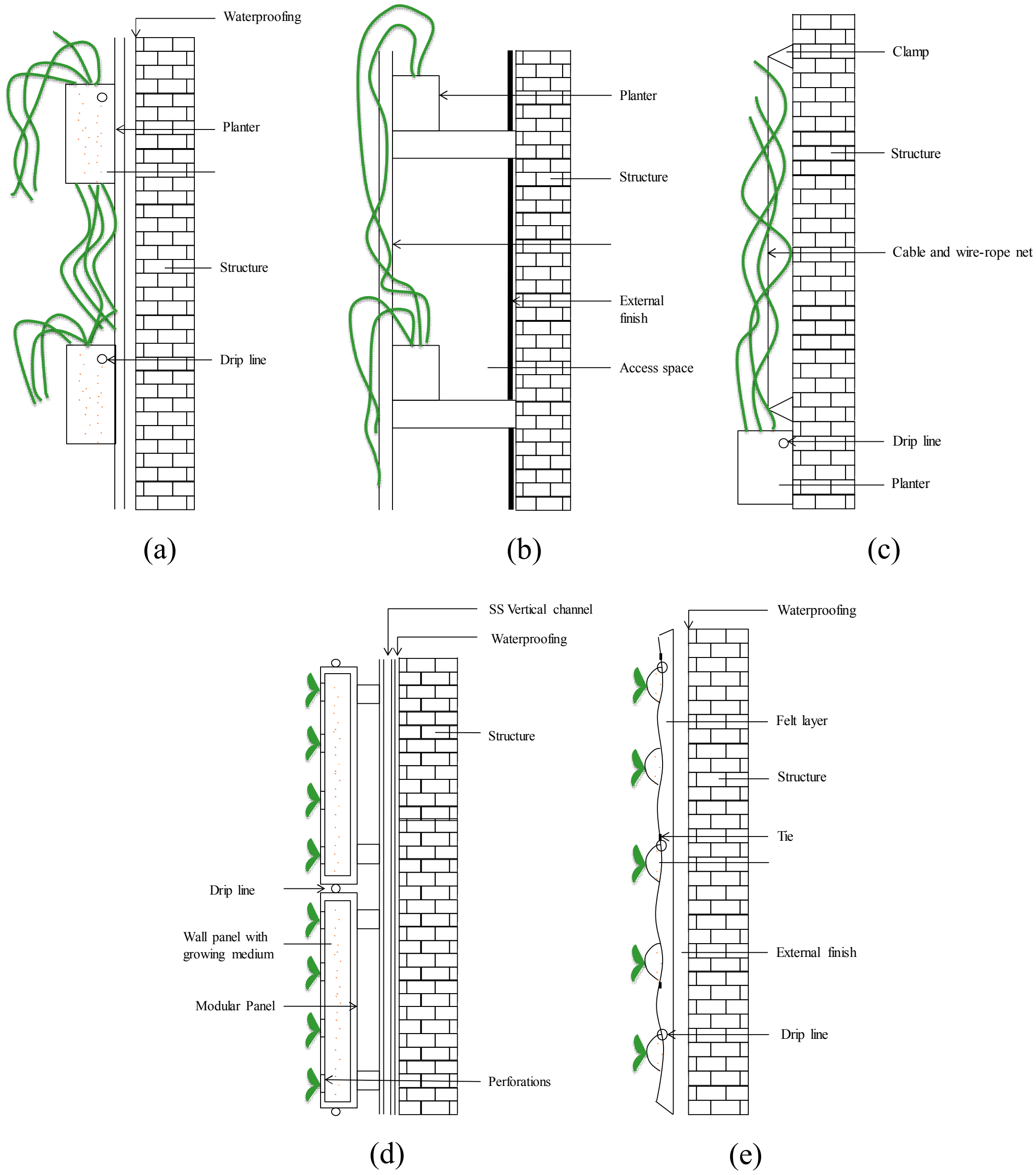
The major elements of VGS include plants, growing media, structures that support and attach plants to the facade, drainage and irrigation (Manso and Castro-Gomes, 2015). Usually VGS have vegetation that are either rooted within those structures or are able to survive independently on the structure without the need to root in surrounding soil (Perini, *et al.*, 2013). The modern systems may be formed by panels and/or geotextile felts, sometimes pre-cultivated, and are fixed to a vertical support or on the wall structure. The panels and geotextile felts provide support to the vegetation by upholstering plants, ferns, small shrubs, and perennial flower. Panels of varying sizes and types, with holes in which the substrate and plants are located, are fixed to the wall.

2.1 Classification of VGS

In general, VGS can be classified into two main groups according to the growing method and configuration (Manso and Castro-Gomes, 2015; Perini, *et al.*, 2011):

- *Green facades*: based on climbing plants attached themselves directly to the building surface, or indirectly supported by cables or trellis. Plants can grow upward or downward the vertical surface.
- *Living/Green walls*: constructed from modular panels, each of which contains its own soil or other artificial growing mediums (substrate-based or hydroponics). They can allow the integration of greening into tall buildings and a rapid coverage of vertical surfaces.

Figure 2 shows five basic types of VGS with different configurations. Types (a), (b) and (c) are green facades and types (d) and (e) are living/green walls. Based on the variation of elements used in the greening construction, the systems may be designed as facade-supported green walls or facade-integrated living walls. In some architectural design for high-rise buildings, stepped terraces and cantilevering tree balconies can also be integrated with the VGS (Wood, Bahrami and Safarik, 2014; Giacomello and Valagussa, 2015).



(a) climbing or hanging system, (b) climbing or hanging system with trellis, (c) cable and wire-rope net system, (d) modular panel system, (e) bag or felt system

Figure 2. Five basic types of vertical greening systems

Based on the installation location and settings, the systems may also be named as:

- *Interior green or indoor living walls*: located in completely enclosed spaces, or semi-enclosed areas with access to natural daylight and air through windows and/or skylights.
- *Spontaneous living walls*: natural and spontaneous growing of plants on wall structures, slopes and retaining walls.

For indoor greening applications, which are developing very fast in the commercial market nowadays (such as in shopping malls, offices and airports), special considerations for indoor humidity, plant growth and maintenance are needed, such as artificial lighting and irrigation (Hui and Ma, 2017). In fact, Wang, Er and Abdul-Rahman (2016) pointed out that indoor

VGS can provide aesthetic and fashion function for the indoor environment. At present, high construction and maintenance cost is still the main obstacle for VGS.

2.2 Environmental Benefits and Value

Usually, VGS is implemented for its aesthetic, environmental and economic value. They can protect facades and offer similar benefits to those gained from installing a green roof (Köhler, 2008). VGS can be used as a passive building design solution for energy saving, contributing to building sustainability performance (Pérez, *et al.*, 2014). The vegetation can influence the microclimate, absorb solar radiation, provide shading and evaporative cooling effects (Manso and Castro-Gomes, 2015). In recent years, many research efforts have been made to study the ecological and environmental implications of VGS (Pérez-Urrestarazu, *et al.*, 2016), developing more knowledge on the possible benefits of VGS under different climatic and urban conditions. A concise summary of the potential environmental benefits of VGS is given in Table 1. More information can be found in the relevant research publications.

Table 1. Environmental benefits of vertical greening systems

Mitigate urban heat island	Create natural habitat
Enhancing building's thermal performance	Increase biodiversity and ecological value
Reduce heat flux and save cooling energy	Facilitate stormwater management
Filter air pollutants and improve air quality	Insulate and absorb sound
Protect facades and building structure	Allow urban farming and social functions

It is found out that some of the environmental benefits and impacts of VGS cannot be measured and quantified easily, such as urban heat island, biodiversity and natural habitat. To examine the key factors of environmental benefits of VGS, three major aspects are elaborated as shown below.

(a) *Thermal performance*

The vegetation of VGS has an important impact on the thermal performance of buildings and will influence the urban micro-climate, both in winter and summer (Eumorfopoulou and Kontoleon, 2009). Plants absorb a significant amount of solar radiation for their growth and biological functions, resulting in cooling potential on the building surface. VGS can cool internal building temperatures, reduce building energy use (for cooling and heating) and facilitate urban adaptation to a warming climate (Hunter, *et al.*, 2014). These effects could be studied by experimental methods and/or computer modelling. Figure 3 shows the infra-red photos of a vertical greening project in Hong Kong. To develop the models for computer simulation of thermal performance of VGS, the heat transfer process and mechanisms should be defined. The three mechanisms of thermal regulation performance of VGS are shading effect, evaporative cooling (or evapotranspiration) and inhibition of wind (Hui and Zhao, 2013). The key factors influencing the heat transfer process on VGS include weather conditions, plant species, orientation and proportion of plant-covered wall layer. It is believed that the moisture content in substrate shows a strong association with the cooling effect mediated by evapotranspiration. Therefore, maintaining proper substrate moisture content is conducive to both heat flux reduction and cooling energy saving.

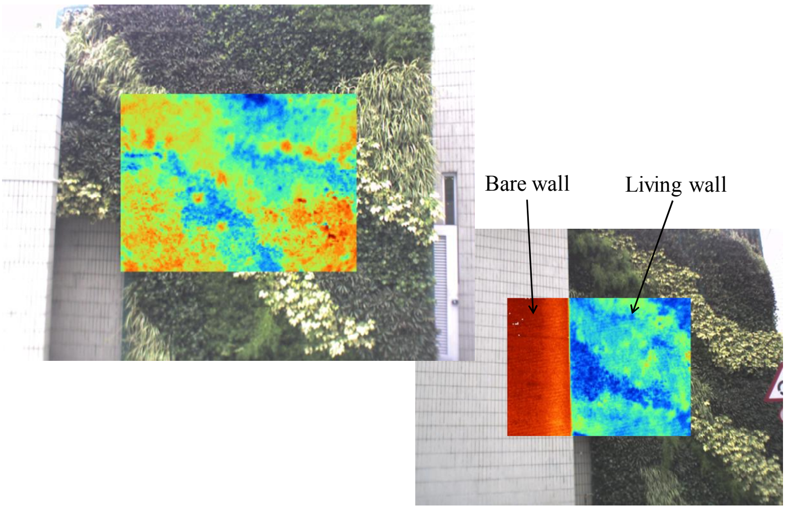


Figure 3. Infra-red photos of vertical greening

(b) *Energy saving performance*

Feng and Hewage (2014a) indicated that the performance in energy saving of VGS has significant impact on the green building performance. In general, greenery systems (such as green roofs, VGS, terrace planting and sky gardens) are considered as a promising solution for making buildings more energy efficient (Raji, Tenpierik and van den Dobbelsteen, 2015). For tall buildings, VGS provide great potential in reducing energy consumption in buildings, especially in the cooling periods by reducing heat flux and solar radiation (Pérez, *et al.*, 2014). However, in cold climatic regions or winter months, green vegetation is not so cost-effective in heating energy saving and thermal insulation because usually only a small portion of heat loss can be reduced by adding the greenery (Feng and Hewage, 2014a). To optimise the energy savings, some aspects of VGS must be studied carefully, such as which species are the most suitable for each climate, influence on energy savings of the facade orientation, foliage thickness, presence of air layers, substrate layer composition and thickness (Pérez, *et al.*, 2014; Safikhani, *et al.*, 2014).

(c) *Air quality performance*

The particle/aerosol deposition and filtering effects of vegetation have been studied by Ottelé, van Bohemen and Fraaij (2010). It is found that the efficiency on the collecting capacity of particles (aerosols/particulate matter) out of the air by vegetation depends on the plant variety (shape and surface of the leaves, deciduous or evergreen plants), structure of the vegetation (width and altitude, roughness, porosity or penetrability), exhibition (source of the component, exhibition level), location (distance to the source of emission, presence of building structures), and circumstances (growing circumstances, micro-climate). The air quality performance of VGS is influenced by the types of materials and plants chosen, as well as the external factors, such as climate and building type (Feng and Hewage, 2014b). Both outdoor and indoor air quality may be affected by the vegetation.

Green vegetation can reduce number of particulates (such as PM10, PM2.5) in the outdoor air and help absorb toxic gas emitted by vehicles or machines. Together with the other elements of green infrastructure, VGS could reduce street-canyon air pollution in urban cities (Pugh, *et al.*, 2012). For indoor air quality, vegetation not only can absorb carbon dioxide and release oxygen through photosynthesis, but also can reduce air-borne contaminants such as nitrogen oxides, volatile organic compounds (VOCs), and dust. When living wall is applied indoor, it can filter the contaminants released from the ventilation systems and capture the airborne pollutants from carpet, furniture and other building elements (Wang, Er and Abdul-Rahman, 2016). Indoor plants can also reduce the dust levels (beneficial to occupants, computers and other electronic equipment), stabilize humidity and temperature, and reduce noise. It should be noted that the actual air quality performance will vary depending on types of plants, living wall design and indoor environment.

3. ASSESSMENT OF ENVIRONMENTAL PERFORMANCE

In recent years, many researchers have tried to develop scientific methods for assessing the environmental performance of VGS. Ottelé, *et al.* (2011) have conducted a comparative life cycle analysis for green facades and living wall systems in the Netherlands to identify environmentally preferable choice. Zia, Zia and Larki (2013) have performed a comparative life cycle analysis for green wall systems in Iran. Perini and Rosasco (2013) presented a cost-benefit analysis of different vertical greening systems in Italy to determine which ones are more economically sustainable. Feng and Hewage (2014b) have conducted a lifecycle assessment of living walls in Canada based on air purification and energy performance. Pulselli, *et al.* (2014) have developed an emergy based evaluation of environmental performances of living wall and grass wall systems in Italy. Pan and Chu (2016) has tried to quantify the environmental benefits and burdens of a commercially available VGS in a public housing estate in Hong Kong. All of them focused on outdoor facade greening.

For indoor applications, Hui and Ma (2017) has developed an analysis of environmental performance of indoor living walls using embodied energy and carbon, which is based on life cycle assessment (LCA) principles using SimaPro modelling. It is found that indoor living walls could be more environmentally sound if recycled materials, renewable energy and sustainable design and maintenance practices are used. When developing the theoretical models for studying the environmental impacts of VGS, it is important to consider the boundary conditions of the LCA. Basically, the boundary conditions must be relevant in relation to the purpose of the LCA. Figure 4 shows three common boundary conditions: (a) cradle to grave, (b) cradle to site, and (c) cradle to gate. To define what is included or excluded in the LCA for VGA, it is necessary to make reasonable assumptions and judgements on what and how the environmental benefits and burden should be considered.

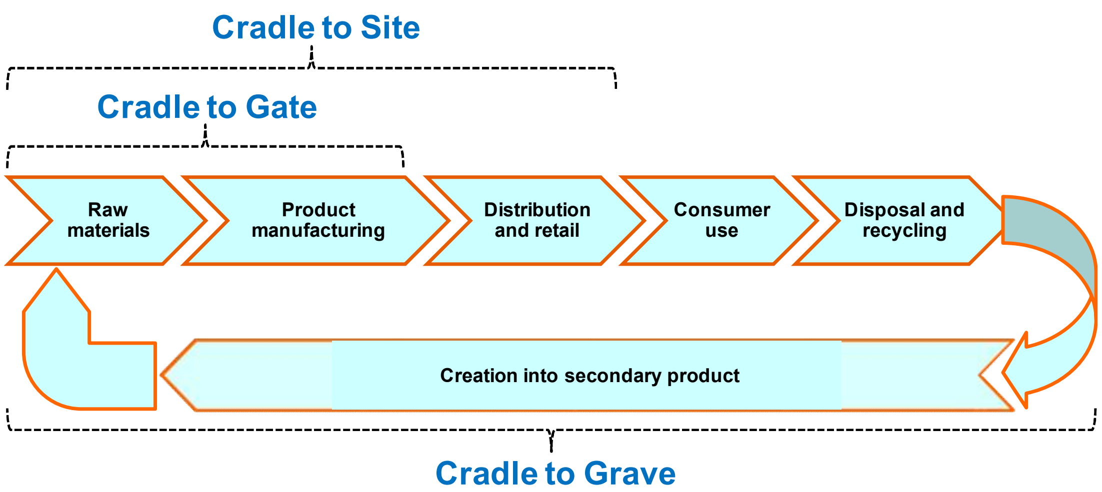


Figure 4. Common boundary conditions for life cycle assessment

3.1 Environmental Burden and Life Cycle Impacts

Despite the environmental benefits as mentioned before, VGS have been criticized for environmental burden, such as consumption of materials, excessive use of water, energy and chemicals for fertilization (Ottelé, *et al.*, 2011; Wang, Er and Abdul-Rahman, 2016). As compared with green roofs, they usually require high construction costs and are more difficult to access and maintain. Often, the design and construction procedures are more complicated. For example, the panel structure of living walls needs a supporting frame and may include complicated irrigation system with sensors. Moreover, the aggressive growing of plants on the facade can possibly damage the walls. VGS can attract insects and its overgrowing sometimes looks wild too. In addition, VGS may bring unwanted animals and humidity, which can destroy the constructed elements.

A comparative analysis is often used to evaluate the environmental performance of different types of VGS and/or system design configurations so as to determine the environmentally preferable option(s) or analyse the key influencing design factors. In order to develop the LCA model and quantify the system performance, a functional unit should be defined to serve as a basis for comparison of the greening alternatives (Zia, Zia and Larki, 2013). The results of the analysis are expressed as the environmental profile which includes a set of environmental impact categories accumulated over the service life. The different systems and materials can have an influence on the environmental burden either positively or negatively. In general, the environmental calculations for the VGS are divided into three main life cycle stages: embodied stage, construction stage, and operation stage (Hui and Ma, 2017). In terms of life cycle environmental impacts, the total environmental profile is built up by four main components: (a) materials, (b) transportation, (c) construction, and (d) operation.

Although the assessment results are limited by the modelling assumptions and evaluation conditions set out in the LCA, they can still provide useful information and tools to understand and improve the environmental performance of VGS. In order to enhance the environmental performance of VGS, those elements that can significantly impact the environment should be identified and managed effectively. For instance, Feng and Hewage (2014b) found that the felt layer system is not environmentally sustainable in air cleaning and energy saving when compared to the trellis system and modular panel system.

3.2 Key Factors of Environmental Performance

For outdoor facade greening, many researchers have discovered the fact that materials and waste of the VGS contribute a significant portion of the overall environmental impacts (Feng and Hewage, 2014b; Ottelé, *et al.*, 2011; Zia, Zia and Larki, 2013). To achieve more sustainable VGS, environmental friendly materials, installation and growing methods should be adopted as much as possible. For example, materials and products that are closer to the site with less delivery requirement should be considered in the construction stage. Materials that could be recycled or reused should be applied. Vegetation that consumes less fertilizer with lower replacement should be used. Green residues from plant replacement and trimming/pruning should be treated to produce compost and added to agricultural soil. Usually, the indirect greening system has a high impact profile for the supporting materials because the support structure and replacement both for plants and material have a high contribution on the negative environmental impacts.

For indoor living walls, however, the operation related environmental impacts often dominate the total environmental profile (Hui and Ma, 2017). It is because over the system life time, significant energy, water and other resources are required for the artificial lighting, irrigation and maintenance in the indoor environment. To manage and reduce the adverse environmental impacts, sustainable strategies and equipment should be considered and applied, such as energy efficient lighting (lighting emitting diode, LED), renewables (solar or wind energy), water recycling system (rain water or waste water), composting systems (from green residues), and environmentally-responsible maintenance practices. By integrating the vegetation with the building envelope (such as for double-skin green facade and adaptive solar control) and/or building services systems, their functionalities can be combined and the overall environmental performance and cost effectiveness may be improved (Sheweka and Mohamed, 2012). For instance, Abdo (2017) has studied and demonstrated a living wall retrofit by integration with heating, ventilating and air-conditioning (HVAC) systems. The integration can enhance air humidification, biofiltration and indoor oxygen generation.

4. DISCUSSIONS

In many cities in the world including Hong Kong, the lack of good design and implementation guidelines for VGS has affected the quality and performance of the greenery systems. Although VGS are becoming more and more popular in the market, it is believed that most building owners and decision makers do not fully understand the environmental and ecological implications of the greening systems. Very often, the common reasons that they accept now for adopting VGS are:

- Aesthetic (ornamental, how it looks and if it is appealing to the customers)
- Cognitive (perception of green image and associated meaning)
- Experiential (trial use and pilot project)
- Fashionable (design trends and popular style)
- Financial gains (incentive scheme and green building credit points)

For sustainable building design in smart cities, it is important to understand and enhance the environmental performance of VGS. A balanced view of the environmental benefits and burden, as well as an appreciation of the ecological and social factors are helpful for planning and designing effective greening systems and infrastructure.

4.1 Urban Planning and Ecological Design

As indicated in the previous sections, the key issues that determine the benefits from VGS are dependent on geographic location, climate, building geometry, building orientation, plant species, configuration and components of the greening system. For urban communities, Zupancic, Westmacott and Bulthuis (2015) found that urban green spaces can provide cooler, cleaner air at the site, neighbourhood and city level because they have a natural ability to filter pollution from the air and reduce local air and ground temperature. These ecological benefits are directly related to the size, quality and density of the green space. In effect, closely spaced and connected smaller green spaces can provide greater cooling effects to adjacent urban areas than large individual parks with open grass areas. Therefore, if the VGS in the city or district are properly designed and connected, they can create significant cooling potential for mitigating urban heat island.

For the control of greenhouse gases in the atmosphere, the phenomenon of carbon dioxide sequestration by plants embedded in VGS can be utilized for managing the carbon cycle and mitigating climate change in urban areas (Marchi, *et al.*, 2015). Usually these plants do not demand high water and large space. This phenomenon includes a series of processes, from planting and growth of herbaceous plants in the VGS to the end of their lives, when compost is produced from green residues and is added to agricultural soil. The amount of carbon dioxide removed from the atmosphere is the portion finally stocked in the soil in the form of microbial biomass.

To achieve the ecological benefits and reduce the construction/maintenance costs, choosing suitable plant species and substrate is very crucial in VGS (Ma, *et al.*, 2013). The amount of maintenance a client is willing to provide is an important design factor that may impact the selection of the type of system and plants installed. Cameron, Taylor and Emmett (2014) have pointed out that different plant species have dissimilar cooling capacity and the mechanisms for the cooling potential may vary with the design of the greening system. Plant physiology and leaf area/morphology should be considered when selecting species to maximise cooling in VGS applications (Brandwein, 1987). Moreover, VGS offer a great potential to enhance urban biodiversity (Madre, *et al.*, 2015), but not all forms of greenery benefit urban biodiversity to the same extent (Chong, *et al.*, 2014). In order to manage the total biodiversity in an urban area, it is important to mimic the ecological functions of natural vegetation and design the urban environment for a greater variety of animals with different adaptabilities.

4.2 Social Factors and Urban Greenery

Francis and Lorimer (2011) indicated that successful utilization of living roofs and walls for urban reconciliation ecology will rely heavily on the participation of urban citizens. Public participation and support for urban greening are important bottom-up techniques for urban conservation. It is believed that urban greenery can improve mental health and wellbeing. Having VGS and greenery views in cities help to relieve stress and pressures cumulated by living and working in busy and crowded cities. This improves the quality of social living, such as less mental problems and lower crime rate. Nakahashi and Iwasaki (2008) have studied the psychological effect of vertical greening in Japan and indicated positive correlation between the aesthetical value and social well-being (therapeutic effects).

Based on 25 real life projects in Malaysia, Bakar, Mansor and Harun (2013) have studied the potential for VGS to be introduced as a new form of sustainable public art in urban cities. Besides aesthetical value, they can promote the sense of community, celebrate the sense of place, and address community needs, social implication and educational value. As a result, VGS can contribute to artistic expression, improve the quality of life and creativity as a work of art in the urban landscape.

On the perspective of urban agriculture and gardening, VGS can also provide local fruit and vegetation for the community. Basher, *et al.* (2016) has investigated the use of edible VGS to improve thermal performance of buildings in tropical climate (Malaysia). They found that VGS with winged bean plants can also be installed in multi-storey buildings and residential balconies to reduce the building surface temperature and provide food production. In fact, if a suitable space is available in the building, even mobile growing walls with movable and modular design can be used to promote urban agriculture and VGS. Figure 5 shows two examples of edible vertical gardens.

Figure 5. Examples of edible vertical gardens
(Image source: www.lifeisagarden.com.au and www.florafelt.com)

5. CONCLUSIONS

VGS are vegetated structures fixed on building facades and can provide good aesthetic effects and other environmental and ecological benefits. They can offer multiple benefits as innovative components of urban green infrastructure and help increase greenery in built environments lacking green areas. As VGS are being increasingly used in the commercial market and urban landscape, it is of vital importance to use resource-efficient design in which both the technical and plant design are sustainable. Although these greening systems are becoming popular nowadays, they are still evolving and more knowledge on their environmental performance and practical implementation is required.

It is believed that VGS can be an innovative way to better integrate nature into our ever-expanding urban cities and bring nature closer to humans. The design, installation, and maintenance of VGS are vital to the long-term health and sustainability of our smart city environment. To enhance the environmental performance and potential benefits of the vertical greening, the life cycle environmental impacts, integrated sustainable technologies and holistic ecological and social factors should be considered carefully in the planning, design and maintenance of the systems.

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