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ABSTRACT *Urban development is causing environmental and social concerns that are compromising human welfare and the sustainability of cities. New urban greening concepts are being developed to mitigate these problems in a sustainable and natural way. Vertical greening systems can be defined as structures that allow vegetation to spread over a building facade or interior wall. These systems are becoming popular though they are still evolving and more knowledge on some of their particular impacts is required. In the last five years, the number of studies published in the scientific literature on this topic, especially involving living walls, has significantly increased. This scientific interest has corresponded with an increased and parallel attention by the general public. This work offers a broad description of the different systems and a comprehensive review of the particular benefits of these green infrastructures. Knowledge gaps and shortcomings have also been identified and discussed.*

KEYWORDS *living walls; green facades; vertical garden; green wall; sustainable construction; urban greening*

Introduction

Not long ago, cities were surrounded by broad extensions of rural areas. Nowadays, rural populations are declining while urban populations are continuously increasing, leading to a rapid expansion of cities. This massive urban development is altering the land surface by concentrating materials which effectively retain heat and create impervious surfaces, thus affecting urban local climate and urban hydrology. Moreover, tall buildings provide multiple surfaces for the absorption of solar radiation that is subsequently reradiated as heat, thus enhancing the efficiency with which urban areas are warmed up. This fact, linked to the waste heat generated by energy use, leads to temperature increases in cities known as urban heat island (UHI) effect (Environmental Protection Agency, 2008), a precursor of other problems ranging from human health issues to higher energy consumption due to the overuse of air conditioning systems (Bass and Baskaran, 2001).

Furthermore, urban areas are known to be major concentrators and emitters of multiple contaminants resulting from human activities within the built environment (Diamond and Hodge, 2007). As a result, carbon dioxide (CO_2) and harmful toxins such as Volatile Organic Compounds (VOCs) frequently reach damaging

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atmospheric levels in some metropolitan areas (OMS, 2011). Some VOCs are known carcinogens and have been associated with sick building syndrome (Kostainen, 1995). Besides these issues, other environmental and ecological problems arise because of unsustainable urban development (e.g., limited green spaces, biodiversity loss, alteration of landscapes, etc.) (Frank, 2000).

As a consequence, new building strategies and methods are needed to minimize the deleterious environmental effects of urban infrastructures while improving their social and economic value (Li et al., 2007). Urban greening initiatives are a way of achieving ecological goals while reducing the undesirable effects of urban growth (Gomez et al., 1998; Westphal, 2003; Currie and Bass, 2005). However, the development and expansion of cities has traditionally been guided by the criterion of maximizing the constructed area to increase profitability. This leads to situations in which enjoying open green areas is becoming a difficult task for dwellers of many cities. The use of the outer surfaces of buildings offers the possibility of increasing the vegetation presence in densely-built urban areas that have a minimum of traditional horizontal green spaces. As a result, planting on roofs and walls turns out to be an innovative and rapidly developing field towards sustainable and environmental construction (Bass and Baskaran, 2001). In addition, given that the potential area for vertical greening is significantly higher than the surface area available horizontally, the capacity to amend negative environmental issues seems to be greater with vertical greening systems (VGSs) than with green roofs (Emilsson et al., 2007). Therefore, the current interest in VGSs as means of improving urban environments is soaring (Köhler, 2008). The objective of this paper is to provide a state-of-the-art view on VGSs as well as a critical discussion of the potential of these novel green infrastructures to meet the goal of increasing sustainability of densely built urban areas.

Vertical Greening Systems: An Overview

Vertical Greening Systems (VGS) are also known as green-wall technologies, vertical gardens, or bio walls. They consist of vertical structures that spread vegetation that may or may not be attached to a building facade or to an interior wall. Attending to the level of complexity, there are several green-wall typologies that range from the simplest configuration to the most complex and high-tech design. Based on the type of vegetation and support structures used, these systems can be divided into two major groups: green facades and living walls (Kontoleon and Eumorfopoulou, 2010; Manso and Castro Gomes, 2015).

In green facade systems, or green screens, the vegetation cover is formed by climbing plants or cascading groundcover (See Figure 1). Specially designed structures can be used to force the plant development through the building's wall, which can serve as support for the climbing vegetation. Normally, green facades are rooted at the base in the ground or in plant boxes, but intermediate planters, fixed to the wall at a certain height or even on rooftops as a falling green cascade, can also be used. Due to the lower diversity and density of plants, green facades normally require less intensive maintenance and protection than living walls (Ottelé et al., 2010).

Living walls are generally more complex infrastructures that involve a supporting structure with different attachment methods. A waterproof backing is required to isolate the living wall from the building in order to avoid problems

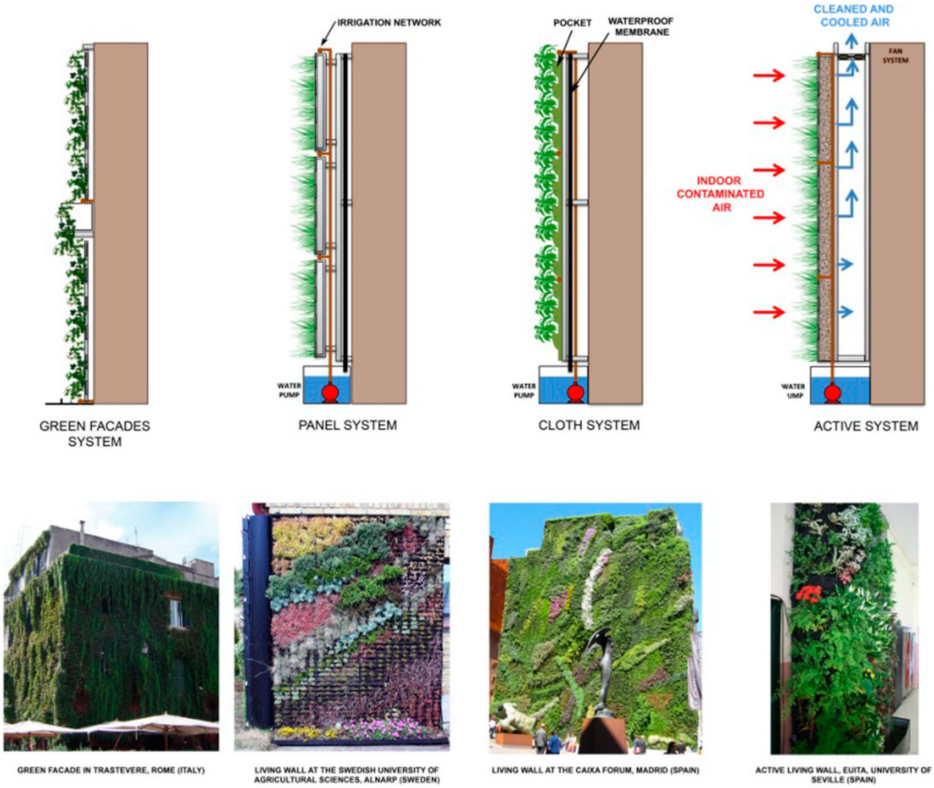

Figure 1: Vertical greening systems: categories and examples

associated with dampness. An irrigation network is also necessary while fertigation, monitoring, and lighting systems are optional.

Cloth (or felt) and panels (or boxes) are the most commonly used vegetation attachment methods to the supporting structure (See Figure 1). Within the panels system there exists the possibility of planting *in situ* once the structure is attached to the wall or using pre-vegetated panels that are prepared before planting in specially designed structures. In each of these cases, the growing medium is allocated inside the pocket (if cloth system is used) or the panel. The systems that use either organic or inorganic growing media along with mineral nutrients to grow plants outside the soil are also known as soilless or hydroponic systems. In some particular configurations, plants are not rooted on growing media, but the roots are directly attached to the cloth, becoming a singular hydroponic system that depends on the irrigation reliability. Overall, the materials used to build vertical structures are highly variable and may support a great variety of plant species (Loh, 2008). Regarding placement and installation, VGSs are usually located outdoors and fixed to the exterior wall of the building. Nonetheless, they can also be built in the interior of the building envelope (termed as indoor living walls) though, in that case, some considerations regarding indoor humidity, lighting, and plant species must be taken into account (Fernández-Cañero et al., 2012).

Even though living walls were initially inspired by the epiphytic plant growth in the tropical forests, over time, it was found that a wide range of plant types could adapt and grow suitably on a living wall. Plants used on living walls can be epiphytic (growing on other plants for mechanical support, deriving moisture and nutrients from the air, rain, and sometimes from debris accumulating around it) or lithophytic (growing on rocks or stony soil and deriving nourishment from the atmosphere). Ferns, succulents, shrubs, and herbaceous and climbing plants can also be used. Over and above ornamental species, there are many successful experiences of planting edible herbs and vegetables to create vertical gardens of lettuce, mints, thyme, strawberries, etc. (Weinmaster, 2009; Utami and Jayadi, 2012). Species selection should not be based solely on esthetic considerations, but should be based on multiple factors such as the system of cultivation, microclimatic conditions, and sun exposure. For example, in an indoor living wall, plants are subjected to very different conditions from those found in an outdoor living wall, therefore the plant species used are usually different. Thus, in any indoor living wall project, regardless of the geographical location, it is common to find species of subtropical and tropical origin, e.g., *Anthurium scherzerianum*, *Codiaeum variegatum*, *Chlorophytum comosum*, *Ficus pumila*, *Nephrolepis exaltata*, *Spathiphyllum wallisii*, or *Syngonium podophyllum.* On the other hand, species used in outdoor living walls vary greatly depending on location, as well as site-specific microclimate (sun and wind exposure, height, etc.). In this way, in a south-facing living wall located in the Mediterranean region, species such as *Allium spp*., *Asparagus sprengeri*, *Dianthus barbatus*, *Felicia amelloides*, *Lavandula dentata*, *Russelia equisetiformis*, and *Tulbaghia violacea* are often found.

Traditionally, the green wall has acted as a "passive" bio filter, but new approaches and technologies are moving towards the integration of living walls (both indoors and outdoors) within the building's air conditioning and ventilation systems. The result is called "active living wall," in which an air current is forced to pass through the green wall and collected afterwards so that the recycled fresh air can be supplied to the building's interior as the air has been cooled, filtered, and humidified by the plants and growing media.

Benefits

Researchers are becoming increasingly aware of the potentiality and positive effects that urban greening initiatives play on numerous aspects of the urban environment. Over the last 25 years, many efforts have been made by the scientific community to shed light on the multiple ecological, environmental, and social benefits of green roof systems (Getter and Rowe, 2006; Takebayashi and Moriyama, 2007; Yang et al., 2008; Getter et al., 2009). This interest has extended over recent years to VGSs to provide responses and further knowledge on their particularities as compared to other urban green infrastructures. What follows is a comprehensive review of the particular benefits of VGSs, focusing on their ecological, environmental, and social implications.

Ecological Implications

Urban areas are known to exhibit, in most cases, lower biodiversity than the pre-urban ecosystem (Pauchard et al., 2006). The need to preserve biodiversity for the continuance of our species and the fact that the land devoted to protected areas is insufficient to prevent biodiversity loss (Laurance et al., 2012) has led to the development of new ecological concepts and ways to preserve Earth's biodiversity. In this context, reconciliation ecology (Rosenzweig, 2003) aims to modify and diversify anthropogenic habitats to support a greater range of species without compromising land use. VGSs, as well as green roofs, represent a good example of the practice of reconciliation ecology, as these infrastructures create habitats for plants and animals on land that is being directly used by humans as living space (Francis and Lorimer, 2011). They enhance urban biodiversity and thus the urban environment (Whitford et al., 2001) by allowing spontaneous vegetation to colonize these systems (Dunnet et al., 2008). As they can mimic natural vertical habitats such as cliffs or vegetated waterfalls (Madre et al., 2015), they provide habitats (Brenneisen, 2006) for birds and insects responsible for numerous functions and ecosystem services, such as pollination or biological control (Madre et al., 2015). They may also be used to grow species that can address specific functions that are missing in the urban environment, mostly oriented to plants' ability to remove air pollutants (Francis and Lorimer, 2011). Species such as *Adiantum raddianum*, *Chrysantheium morifolium Dieffenbachia spp.*, *Dracaena godseffiana*, *Epipremnum aureum*, *Hedera helix*, *Marraya* sp., *Nephrolepis exaltata*, *Philodendron sp.*, *Rhododendron obtusum*, *Sansevieria trifasciata*, *Spathiphyllum maunahoa*, and *Vriesea splendens* have that capacity (Loh, 2008; Weinmaster, 2009). But, despite the number of existing studies performed on the ecological implications of green roofs, observations focused on living walls are still anecdotal. It is, therefore, desirable that new and specific wall-oriented trials are conducted to disentangle the real ecological potential of living walls as well as the optimal design details that allow enhancing urban biodiversity.

Environmental Implications

The use of plants to improve the quality of their surrounding environment is becoming a key design consideration in modern building developments that seek not only an esthetic impact but also a means of providing environmental services, such as natural cooling of air, water filtration, and mitigation of several environmental problems (Ushada et al., 2007; Birkeland, 2009; Ushada and Murase, 2009). In the case of indoor living walls, a building's interior environment may benefit from the reported positive effects of vegetation on air quality (Wolverton and Wolverton, 1993; Raza and Shylaja, 1995; Todd, 2005), which are not only related to the plants' ability to adhere particles from air but also to their efficiency (along with microorganisms found in the substrate) in taking up air pollutants (Miyawaki, 1998). In the latter process, known as biofiltration, carbon dioxide (CO_2) and harmful toxins are retained by both plants and substrate as the air is drawn through the living wall. In an experiment performed with these biofilters, indoor air concentrations of three noxious VOCs (toluene, ethylbenzene, and oxylene) were significantly reduced when air was forced to pass through the vegetation (Darlington et al., 1998). Indoor living walls can, therefore, be used to supplement traditional ventilation techniques to maintain indoor air quality (Darlington et al., 2001). The biofiltration effect can be enhanced when the air is mechanically forced to go through the vegetation and substrate using a permeable structure leading to an active living wall. However, the design process of these systems is somewhat more complex, as it requires prior assessment and more scientific knowledge on the behavior of some of their principal components, such as the substrate used for plant development (Franco-Salas et al., 2012).

Besides air pollution mitigation, air temperature and humidity are other key variables of indoor air quality, very much related to human comfort, which may be altered by indoor living walls (Fang et al., 1998; Darlington et al., 2000). In warm climates, temperature reductions up to 4–6°C have been observed in the surroundings of an indoor living wall (Fernández-Cañero et al., 2012). The evapotranspiration process of plants and substrate requires energy that is taken from the indoor air, thus decreasing air temperature and increasing humidity (ASHRAE, 2009). This physical process generates the so-called "evaporative cooling," which depends, among others factors, on the vegetation type and exposure. During the evaporative cooling of air, indoor air humidity is also increased. Given that indoor air is usually too dry, particularly when internal heating or cooling systems are being used, the humidity increment of indoor air provided by the living wall may be beneficial. Nonetheless, under certain conditions (e.g., humid locations), ventilation may be required to avoid health problems associated with excessive humidity (Husman, 1996; Ren et al., 2002).

When installed on the exterior walls of buildings, living walls have been reported to have an important effect on the thermal performance of buildings and on the urban environment. As reviewed in Pérez et al. (2011) and more recently in Hunter et al. (2014), exterior VGSs may modulate indoor temperature through a combination of four fundamental mechanisms: interception of solar radiation by vegetation; thermal insulation provided by the vegetation and substrate; evaporative cooling that results from evapotranspiration; and modification of the wind pattern in the building envelope. The successful combination of all these processes has demonstrated the potential for exterior living walls to be used as passive energy-savings systems (Pérez et al., 2011). Susorova et al. (2013) proved that a plant layer added to the facade can improve its effective thermal resistance. Mazzali et al. (2013) registered a difference of up to 20°C in the external temperature of a wall depending on the existence of a living wall covering it. Also the incoming (positive) heat flux through a bare wall was found to be higher compared to the living wall. Therefore, with the appropriate selection and placement of vegetation, an important reduction of cooling energy demands can be achieved (Meier, 2010), as the thermal gap between environment and comfort temperature decreases. Recently, Wong et al. (2009, 2010a) pointed out the potential thermal benefits of VGSs in reducing the surface temperature of buildings facades in a tropical climate, leading to a reduction in cooling load and energy costs. The adoption of plant-covered wall designs in a Mediterranean climate also appears to be a suitable strategy to reduce energy consumption of buildings during the cooling period (Eumorfopoulou and Kontoleon, 2009; Kontoleon and Eumorfopoulou, 2010). In a modeling work conducted for the city of Toronto (Ontario, Canada), the shading and cooling effects of VGSs reduced the energy needed for cooling by approximately 20 percent (Bass and Baskaran, 2001), though potential cooling energy savings of up to 60 percent during warm summer days have also been described (Parker, 1987). Despite all these positive outcomes reported regarding energy savings in buildings, other authors such as Archer (2011) state that the overall thermal benefits of living walls, as compared to a well-insulated building wall, can be small. Therefore, while the energy-saving benefits of living walls retrofitted on poorly-oriented and insulated buildings seems generally accepted, a full financial assessment of the potential costs and benefits should be accomplished before implementing these systems in well-insulated modern buildings (Castleton et al., 2010).

Sometimes, employing deciduous climbers to offer seasonal regulation of shading may be interesting (Hoyano, 1988; Ip et al., 2010), especially in winter when energy consumption may increase because of the shadow produced by the vegetation on the building (Pérez et al., 2011). The capacity of VGSs to limit the diurnal fluctuation of wall surface temperatures is also valuable in prolonging the lifespan of building facades and slowing down wear and tear as well as cost savings in maintenance and replacement of facade parts (Wong et al., 2010a).

Given that plants absorb a considerable quantity of solar radiation for their growth and biological functions, such as respiration, transpiration, and photosynthesis (Kontoleon and Eumorfopoulou, 2010), VGSs can also play an important role in shaping the urban microclimate (Wong et al., 2010a). Indeed, the combined use of vertical greening structures and green roofs are increasingly being used as a new "bioclimatic" design concept of buildings in order to alleviate the urban heat island effect (Gomez et al., 1998; Ip et al., 2010; Sheweka and Mohamed, 2012) in cities by reducing the amount of reradiated heat (Bass and Baskaran, 2001). As an example, a temperature reduction of 8−9°C has been observed in an urban canyon (tall buildings on both sides of the street) when walls and roofs were covered with vegetation in an experience conducted in Hong Kong, the wider the canyon is, the weaker the effect on temperature decrease (Alexandri and Jones, 2006). Similarly, Wong et al. (2010a) found promising results on the use of VGSs to cool the ambient temperature in building canyons, albeit their effects on ambient temperature were found to depend on specific systems. A major consequence of the effects of living walls on ambient temperature of street canyons is the fact that air intakes of air-conditioning at a cooler ambient temperature translate into savings in energy cooling loads (Wong et al., 2010a).

Living walls can be also used as noise barriers (Ottelé et al., 2010), as the substrate where plants grow has a sound-absorbing effect and provides acoustic benefits derived from noise isolation (Azkorra et al., 2015); the broader the greenery coverage is, the higher the sound absorption. When the living wall is installed internally, it may also be useful in protecting speech privacy (Wong et al., 2010b). A well designed system can also have positive effects on urban hydrology, avoiding sudden discharges of storm water to the sewers when rainfall water is harvested on the roofs to irrigate the living wall, especially if it is combined with green roof technologies that act as water buffers (Carter and Jackson, 2007).

Aesthetic and Social Implications

The use of VGSs is also a highly impactful way of transforming the urban landscape (Wong et al., 2010a), incorporating advanced materials and technology to promote sustainable building functions (Köhler, 2008). Creative architectural solutions that implement greenery elements either for the restoration of old buildings or in the design of new ones would definitely improve the esthetical aspect of our cities (Elinç et al., 2013). As an example, White and Gatersleben (2011) carried out a study to assess the esthetic impact and the level of perceived restoration that may be achieved by placing green roofs and facades onto homes. The results of the study showed that houses with building-integrated vegetation were more preferred and considered more beautiful, esthetically pleasing, and restorative than those without vegetation. Those conclusions were consistent with the findings by other researchers such as Kaplan et al. (1989) and Van den Berg et al. (2007), who also pointed out the importance of an adequate selection of plant species in the construction of a green roof or living wall from the esthetic point of view.

There are some other "perceived benefits" of these greening initiatives. Sometimes, they provide a place for recreation and retreat where people can enjoy quiet moments amidst dense urbanity (Yuen and Nyuk Hien, 2005). As another example, the service sector tends to offer more environmentally conscious products and services (Rosenblum et al., 2000), so these systems provide an added ecological and esthetic value that is highly appreciated by current clients. In addition, there is an increasing level of social awareness of the benefits of promoting local green initiatives within urban communities for which these systems can have a favorable reception in densely built and populated cities. Indeed, the social component may be enhanced when these technologies are incorporated into the portfolio of "green" options within urban greening movements. The number of initiatives that have successfully implemented the use of new urban greening concepts within urban communities is growing, e.g., the success of the cultivation of vegetables on green roofs (Whittinghill and Rowe, 2012), but the use of VGS has not yet approached that of green roofs. Possibly, in order to introduce them into the social movement of urban agriculture, more affordable and simple-handling systems should be available for "non-expert users."

Discussion

Research about Vertical Greening Systems

In the last five years, the number of authors publishing studies involving VGSs has grown significantly. The scientific interest in this topic has corresponded to an increasing and parallel interest by the general public (See Figure 2). As can be seen from Table 1, the effect of living walls on the thermal performance of buildings has been by far the main topic studied involving VGSs. In fact, during 2014

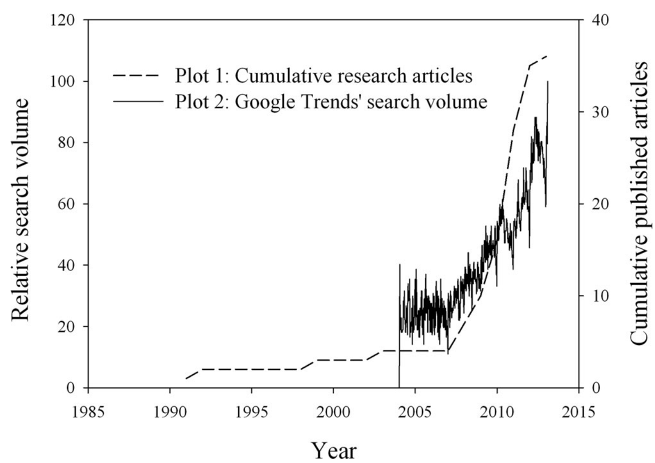

Figure 2: Plot 1: Cumulative research articles published on *Thomson Reuters Web of Knowledge* over the last two decades and on the following topics: "living walls," "green facades," "green walls," and "vertical greenery systems." Plot 2: Relative search volume over time provided by Google Trends tool (Google Inc.) for the following search-terms: "living wall," and "vertical garden." In plot 2, number 100 represents the peak search volume.

and 2015, eight works were published on that topic (three of them review articles). It is important to note that major shortcomings in various areas of knowledge related to management and maintenance of VGSs were detected, such as irrigation engineering and water management (only the recent work by Pérez-Urrestarazu et al., 2014 is available in the scientific literature), plant species selection and performance (with the sole example of Mårtensson et al., 2014), supplemental lighting (exclusively addressed by Egea et al., 2014), and growing media (only approached by Jorgensen et al., 2014). There is also a new area of study regarding insulation properties, durability aspects, and materials involved (Perini et al., 2013). In the case of green facades, there are numerous studies in which these aspects have been analyzed in depth (Kohler, 2008), probably due to their traditional nature and their more extended use.

Which System Should I Use?

Given the existing differences among the VGSs available on the market, it is of great importance to make a correct decision about the type of system that is most appropriate to a certain project. To accomplish this, factors like construction and climatic restrictions, the environmental impact, and the associated costs during its entire lifecycle should be taken into account (Manso and Castro Gomes, 2015).

The first choice to be made is: green façade or living wall? Green façades are much simpler, more economical, and easier to install and maintain. However, living walls offer advantages such as the possibility to use a wider variety of species, allowing complex and more esthetic designs (modeling the shapes using different species), rapidly obtaining a full cover of the wall after installation, and improving temperature and noise insulation. Furthermore, depending on the chosen living wall system, its performance in terms of support structure required, water usage, plants' survival, and insulation or aesthetic effects will be different. For instance, the felt system is more flexible (easier to adapt to the façade) and lighter than the panel one, but plant survival is dependent on reliable irrigation management. Manso and Castro Gomes (2015) thoroughly analyze different systems, exposing their advantages and disadvantages. Jim (2015) compares various systems in terms of several critical design and management issues.

Main Concerns about Vertical Green Systems

In spite of all the advantages and benefits of VGSs previously stated, these technologies also have their detractors who uphold diverse issues against their implementation, such as construction issues, negative esthetic effects, water and energy consumption, as well as design, installation, and maintenance costs.

Regarding the additional structural support required (except the direct cladding green façades), different solutions may be adopted depending on the weight per surface unit of the VGS (usually varying from 25 to 90 kg/m^2). Commercial systems employ multiple solutions to fix the VGS to the wall. One of the most common is the installation of a small auxiliary metal structure attached to the wall by multiple points, leaving a 3–10 cm-wide air gap between the VGS and the wall. This air volume acts as an additional protection, improving the insulation in terms of both dampness and heat transfer. However, some other systems

Table 1: Scientific articles about living walls and their main topics

	STUDY	MAIN SUBJECT OF THE PAPER						
Source	Model (M) or real (R)	Substrate analysis	Thermal effect	Water use & irrigation manage	Acoustic insulation	Perception & esthetics	Valuation & sustainability	Active system
Darlington et al. (1998)	**R**							**X**
Darlington et al. (2000)	**R**							**X**
Bass and Baskaran (2001)	**M**		**X**					
Darlington et al. (2001)	**R**							**X**
Alexandri and Jones (2006)	**M**		**X**					
Wong et al. (2010a)	**R**		**X**					
Wong et al. (2010b)	**R**				**X**			
Wong et al. (2010c)	**R**					**X**		
Archer (2011)	**M**		**X**	**X**				
Jim and He (2011)	**R**		**X**					
Ottelé et al. (2011)	**R**		**X**					
Perini et al. (2011a)	**R**		**X**					
Wang et al. (2011)	**R**		**X**					
Sheweka and Magdy (2011)	**M**		**X**					
Fernández-Cañero et al. (2012)	**R**	**X**	**X**					
Franco-Salas et al. (2012)	**R**	**X**	**X**					**X**
Stav and Lawson (2012)	**M**		**X**					
Veisten et al. (2012)	**M**				**X**		**X**	
Chen et al. (2013)	**R**		**X**					
Ismail (2013)	**M**				**X**			

Mazzali et al. (2013)	**R**		**X**					
Perini and Rosasco (2013)	**M**						**X**	
Van Renterghem et al. (2013)	**M**				**X**			
Bakar et al. (2014)	**R**					**X**		
Cameron et al. (2014)	**R**		**X**					
Feng and Hewage (2014)	**M**		**X**				**X**	
Hunter et al. (2014)[a]	–		**X**					
Jorgensen et al. (2014)	**R**	**X**						
Malys et al. (2014)	**M**		**X**					
Pérez et al. (2014)[a]	–		**X**					
Pérez-Urrestarazu et al. (2014)	**R**			**X**				
Pulselli et al. (2014)	**M**						**X**	
Safikhani et al. (2014)[a]	–		**X**					
Scarpa et al. (2014)	**M**			**X**				
Azkorra et al. (2015)	**R**				**X**			
Carlos (2015)	**M**		**X**					
Davis and S. Hirmer (2015)	**M**							**X**
Djedjig et al. (2015)	**M**		**X**					

[a]Review article.

can be attached directly to the wall as they include a waterproof layer that provides the required insulation. Lately, thinner cloth systems have been employed because of their low weight, which allows for a reduction in the support structure and eases the attachment to the wall. This can be significant because the cost of support structures can vary from 7 to 10 percent of total installation costs, even reaching 12 percent in heavier systems.

The aesthetic value of a living wall is provided by the positive interaction of several factors, of which the initial design and species selection, as well as the definition of an appropriate maintenance program are key factors to attain a satisfactory final appearance. In this regard, the features of the selected system may also have an impact on the asthetic value of the living wall as the plant density (i.e., number of plants per unit area) and, hence, the degree of covering obtained is subjected to the plants' characteristics. Plant mortality also plays an important role in the esthetic value of a living wall, so that the systems with higher mortality rates will, therefore, have an added cost for plants' replacement. Plant mortality rates vary widely among systems and locations, reaching up to 50 percent annually in some cases. Yet, in a well-designed and maintained living wall, the annual rate of plant replacement may vary between 10 to 15 percent outdoors, and 5 to 10 percent for an indoor system. In some cases, the appearance of the VGS is not a major concern. This may be the case of VGS devoted to food production where the ornamental value would be difficult to maintain throughout the year due to the characteristics (e.g., dormancy period) and requirements (e.g., plant density) of horticultural plant species.

Water consumption may be an important determinant due to the increasing shortage of this resource in some places. The amount of water required by these systems, used in plant transpiration and substrate evaporation processes, is tightly related to air temperature and humidity, incoming solar energy, speed of the air flow, vegetation type, and substrate characteristics (thickness, transfer surface, presence of vegetation, etc.) (Franco-Salas et al., 2012). Therefore, good species selection is a key design parameter to minimize water requirements in drought-prone areas. Also, recirculating the irrigation water or mixing it with reclaimed greywater and rainwater may considerably reduce the amount of water required. However, implementing water storage tanks for rainfall capture and/or irrigation water recycling may substantially increase the cost of materials and the installation of VGSs. As denoted by Ghaffarian-Hoseini et al. (2015), one of the main factors inhibiting the use of these systems is the initial capital investment, so the installation and size of water storage tanks as an environmentally friendly and water saving strategy for VGSs must be thoroughly analyzed for each case study and geographical location. For instance, installation of rainwater harvesting systems for meeting residential non-potable water demands in humid regions is expected to be more effective than in urban areas with moderate rainfall, whereas in arid climates their performance seems to be inefficient (Rashidi Mehrabadi et al., 2013). Similarly, Ward et al. (2012) showed that, by optimizing the size of water storage tanks in a humid climate, the payback period of a large building rainwater-harvesting system could be reduced from 11 to 6 years.

Like green roofs, VGSs are also considered to improve urban water quality through storm water retention and filtration (Stav, 2008). However, the scientific evidence of this environmental benefit is still insufficient, as the few existing studies shed contradictory results (Berndtsson, 2010). Although runoff water quality is strongly conditioned by the quality of source water, it becomes apparent that green roofs and VGSs may have negative impacts on runoff water quality through increments in content of nutrients (i.e., compost material and fertilizers acting as pollutants) and/or other contaminants such as pesticides (Berndtsson, 2010).

The energy requirement of most of these systems, mainly due to irrigation pumping and lighting systems (if necessary), is not high. Besides, easily-implemented solutions as attaching solar panels to the structure can provide the energy needed for system operation. In any case, and thanks to the energy savings achieved by the additional insulation provided by VGSs, the energy balance of the building may be positive (i.e., no extra energy may be required if these systems are installed) (Bass and Baskaran, 2001). However, this will depend on the type of system used. For instance, Feng and Hewage (2014) stated that the felt system may not be so environmentally sustainable in terms of energy savings compared to the trellis and the modular panel. But, of course, that would depend on the material used and the number of layers composing the felt system.

VGS design needs to take into account many aspects including the integration with the building envelope, a sustainable material choice, the environmental impact, and the symbiosis between the growing medium and the vegetation (Perini et al. 2013). A good design must also ease maintenance operations, though qualified workers should be employed, especially during construction phases. Fact sheets providing detailed information on the installation process, equipment cost, and maintenance issues, as well as the elaboration of a regulated list of reputable suppliers and installers, could help to lessen some concerns (White and Gatersleben, 2011).

In the last few years, the number of companies offering different urban greening "solutions" has increased considerably, so the range of prices for designing, installing, and maintaining VGS is becoming broader (Perini and Magliocco, 2012). Therefore, the traditional concern about the cost of VGS may progressively become of less importance. For example, the cost of an installed green façade may vary between 100 and 300 €/m^2 (though Perini et al., 2011b, points to prices under 100 €/m^2). In the case of felt living wall systems, the range goes up to 400–650 €/m^2 while modular systems prices vary between 500 and 800 €/m^2. For active living walls, prices increase (850–1200 €/m^2), though some of the benefits obtained are enhanced (especially those related to energy efficiency and indoor air improvement). Operation and maintenance (especially the latter) also entail an annual cost. These costs are highly variable depending on several factors such as the degree of complexity of the system, its covered surface (mainly the height which may imply the use of scaffolding, lifting, or hanging platforms), the system characteristics (for example if using hydroponics, maintenance will be more complex), or the number of operations included in the maintenance service. Perini and Rosasco (2013) used for their work some values that can be used as a reference. For instance, for a simple system using climbers attached directly onto the facade (it will require minimal maintenance and low frequency of intervention) the annual cost may be around 2–5 €/m^2 (pruning once a year). In other more complex systems, maintenance costs are much higher, reaching up to 40–100 €/m^2 per year (even more if the access to the living wall is difficult) including tasks such as pruning, plant replacement, treatments, and maintenance of the irrigation system. One option for reducing maintenance costs is to concentrate operations, though they ought to take place at least four times a year (in each change of season).

Despite the abovementioned costs, several studies have supported the economic viability of these initiatives when the above-referred benefits are considered (Clark et al., 2008; Veisten et al., 2012; Pulselli et al., 2014). Perini and Rosasco (2013) also point out that economic incentives (e.g., tax reduction) could diminish initial investment costs thus allowing a wider diffusion of VGSs. From the market perspective, companies are continuously working on improving or developing new products that allow reducing both initial and maintenance costs by installing cheaper and environmentally friendly materials, by making the installation process easier, and by improving the system performance (e.g., reducing plant mortality) thus reducing the maintenance requirements.

Integral Green Buildings and Vertical Farms: New Urban Perspectives

As discussed in previous sections, the broad range of direct and indirect benefits along with the space availability for their implementation in buildings walls provide many reasons to expect that VGSs may play a key role as green concepts within forthcoming sustainable urban plans. Figure 3 depicts a modern conception of what a fully-integrated green building could be. This green construction would include green roofs, indoor and outdoor living walls, advanced monitoring systems, rainwater collectors, and wastewater treatment plants to reclaim greywater and reuse it for irrigation. Indoor air quality could be guaranteed by means of the biofiltration effect of living walls, while the cooling effect of the active systems would allow lower energy requirements. In the process of making these systems more efficient, plant breeding programs would also play

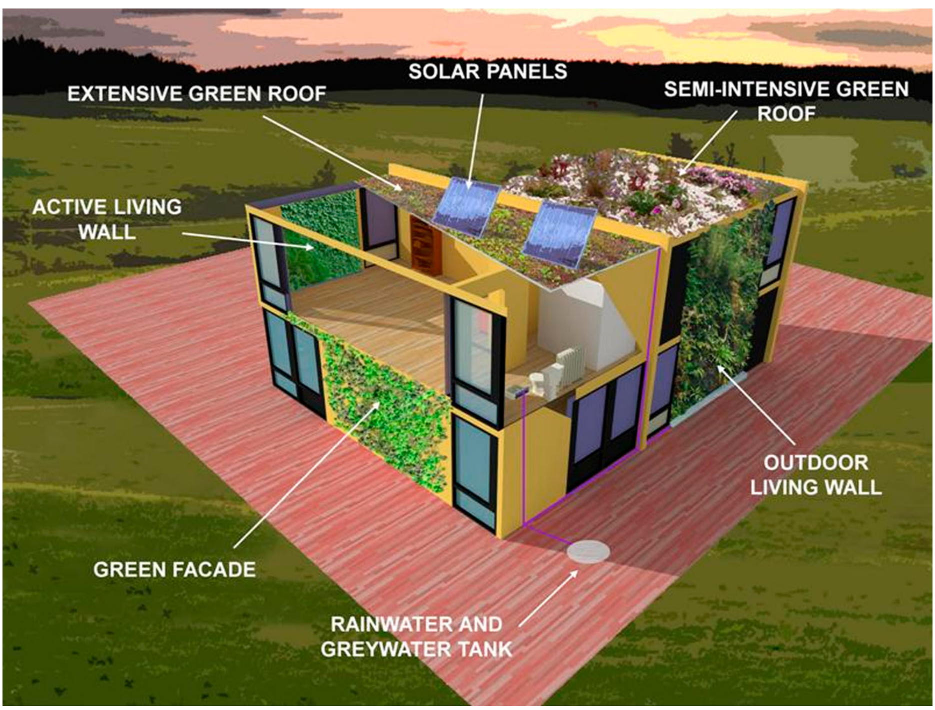

Figure 3: Example of an integral green building

an important role through developing new cultivars that increase, for instance, the plant capacity to sequestrate contaminants from the air.

Other systems that are also becoming popular and that are likely to be part of the future concepts of green cities are so-called "vertical farms" (Despommier, 2009; Abel, 2010). These systems represent a variant of the VGSs herein described that are specifically developed and designed to grow crops that can partly supply urban food requirements. Under these circumstances, the monetary and environmental impact of producing and transporting food from distant places would be reduced. Furthermore, some studies have pointed out that a great increase in productivity with a considerably decrement of inputs could be achieved in urban vertical farms (Despommier, 2011). Although the use of urban vertical gardens to grow crops is still anecdotal, there are already some new projects designed for skyscrapers that include vertical farms (Welte, 2011). Other proposals are centered on converting abandoned urban properties into vertical food production centers.

Conclusions

Vertical greening systems have been used for many years, but nowadays they are becoming more important because of the need for making our cities more sustainable and the increasing environmental concern of their citizens. These systems are evolving, so the traditional compositions of plants and substrates have been combined with new technologies in order to improve their performance and enhance the benefits achieved with them. The success of VGSs in some cities has inspired many designers, engineers, and architects to introduce living walls in their new building projects. Furthermore, the number of researchers studying these systems and the information available about their positive effects and new applications is growing rapidly. These urban greening attempts can also help to alleviate climate change and improve living conditions in our growing cities. Therefore, VGSs have a great potential to contribute to provide a better environment for sustainable cities.

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