Green wall systems: A review of their characteristics

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2 AUTHORS:

Maria Manso
Universidade da Beira Interior

João P. Castro-Gomes
Universidade da Beira Interior

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Green wall systems: A review of their characteristics

Maria Manso*, João Castro-Gomes

C-MADE, Centre of Materials and Building Technologies, Department of Civil Engineering and Architecture, University of Beira Interior, Calçada Fonte do Lameiro Edifício II das Engenharias, 6201-001 Covilhã, Portugal

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Current systems for greening the buildings envelope are not just surfaces covered with vegetation. Greening systems, as green roofs and green walls, are frequently used as an aesthetical feature in buildings. However, the current technology involved in these systems can maximize the functional benefits of plants to buildings performance and make part of a sustainable strategy of urban rehabilitation and buildings retrofitting.

During the last decades several researches were conducted proving that green walls can contribute to enhance and restore the urban environment and improve buildings performance.

The aim of this paper is to review all types of green wall systems in order to identify and systematize their main characteristics and technologies involved. So, it is important to understand the main differences between systems in terms of composition and construction methods.

Most recent developments in green walls are mainly focused in systems design in order to achieve more efficient technical solutions and a better performance in all building phases. Yet, green wall systems must evolve to become more sustainable solutions. In fact, continuing to evaluate the contribution of recent green wall systems to improve buildings performance and comparing the environmental impact of these systems with other construction solutions can lead to an increase of their application in buildings and therefore result in a reduction on these systems cost.

The decision of which green wall system is more appropriate to a certain project must depend not only on the construction and climatic restrictions but also on the environmental impact of its components and associated costs during its entire lifecycle.

Contents

* Corresponding author.
E-mail addresses: mcfmm@ubi.pt (M. Manso), castro-gomes@ubi.pt (J. Castro-Gomes).

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1. Introduction

Current systems for greening the buildings envelope are not just surfaces covered with vegetation. There are several greening systems in the market, like green roofs and green walls, which technology involved is being developed to increase their performance and longevity.

Greening systems, as green roofs and green walls, are frequently used as an aesthetical feature in buildings. However, the current technology involved in these systems can maximize the functional benefits of plants to buildings performance [1]. Greening systems can also make part of a sustainable strategy [2–4] of urban rehabilitation and building retrofitting [5–7].

At a city scale, green roofs and green walls contribute to the insertion of vegetation in the urban context without occupying any space at street level [8]. In fact, covering buildings with vegetation, when applied in a significant urban scale, can improve the urban environment by contributing to urban biodiversity [1,9], stormwater management [10], air quality [11–13], temperature reduction [14] and mitigation of the heat island effect [15,16]. At the same time, the application of greening systems can have, besides the environmental aspects, social and economic benefits. These systems encourage the fruition of urban areas [17], have a therapeutic effect by inducing a psychological wellbeing through the presence of vegetation, improve cities image [7], increase property value [18] and function as a complementary thermal [19] and acoustic protection [20,21].

Green walls have a greater potential than green roofs considering that in urban centers the extent of facade greening can be double the ground footprint of buildings [22].

At a building scale, green wall systems can be used as a passive design solution [23] contributing to buildings sustainability performance [24]. Vegetation has the potential to improve the microclimate both in winter [25], functioning as a complementary insulation layer, and in summer [26], providing shade [27–29] and an evaporative cooling effect [30]. Vegetation absorbs large amounts of solar radiation [31] while the effect of evapotranspiration of plants can further reduce the impact of solar radiation, showing increased humidity levels and surface temperatures lower than hard surfaces [32,33]. Recent studies show that green wall systems have the ability to control heat gains and losses, contributing to improve indoor thermal comfort and reduce energy demands for heating or cooling [15,34–36].

Green wall is the common term to refer to all forms of vegetated wall surfaces. Traditional green wall methods are historically known, since the Hanging Gardens of Babylon and the Roman and Greek Empires. In Mediterranean climates, vines were commonly used to cover pergolas, shading the building envelope, or on building walls, cooling the envelope during summer [37]. Since the seventeenth and eighteenth centuries, mostly in UK and Central Europe, the use of climbing plants to cover building walls proliferated [38]. In the 19th century woody climbers were commonly used as ornamental elements of buildings envelope in European and North American cities [39].

First investigations on green facades were based on botanical aspects [22]. However, since the 1980s a new idea occurred of green facades as contributors to cities ecological enhancement. The garden city movement from the end of the 19th century marked the integration of greening in urban planning. The German Jugendstil movement (Art Nouveau) from the early 20th century encouraged the integration of the house with the garden. During this period emerged some incentive programs for the installation of green facades. In fact, Berlin is an important example, from 1983 to 1997, where around 245.584 square meters of green facades were installed [22].

This paper aims to review the main green wall systems available, systematizing their main characteristics and technology involved. A search of green walls, available internationally on the market or in invention databases (e.g., Esp@cenet, Free Patents Online, Fresh Patents, Google Patents, Lusopat, Wipo – Patentscope), allowed the identification and characterization of most of the existing green wall systems. It must be noticed that this is a field in constant actualization. However, the analyzed solutions constitute a representative universe to identify the main features of green walls in terms of configuration, composition and materials used.

This paper is divided in two main sections. First, a classification of green wall systems, including a definition for different systems according to their characteristics is proposed. Second, the main requirements of different green wall systems in terms of composition, processes of installation and maintenance and their environmental impact and cost are systematized.

In order to compare the several green wall systems and their features, an analysis of their composition is made according to the following items: supporting elements, growing media, vegetation, drainage and irrigation. Additionally, given the importance of these subjects, two subsections were added to focus, first on the different phases of the systems lifecycle, namely on the differences on their installation and maintenance, and second on the environmental performance and cost of green wall systems.

2. Classification and definition

Considering the recent developments in green walls technology it is important to identify and classify all existing green wall systems, according to their construction techniques and main characteristics.

Authors use several nomenclatures when referring to all types of green wall systems. Some use the term “vertical garden” [40,41] others call them “vertical greening systems” [42], “green vertical systems” [23] or “vertical greenery systems (VGSs)” [43]. When referring to direct or indirect green facades, Ottelé et al. and Perini et al. [44,45] used the terms direct greening systems and indirect greening systems, respectively.

Another concept called “Biowalls” was mentioned by Francis et al. regarding the application of green walls in indoor spaces in order to enhance the environment [9].

This concept includes the technology involved in living walls; therefore it can be inserted in this category.

In fact, the concept of green walls refers to all systems which enable greening a vertical surface (e.g., facades, walls, blind walls, partition walls, etc.) with a selection of plant species, including all the solutions with the purpose of growing plants on, up or within the wall of a building [38]. In this paper a classification of green walls according to the different existing systems and their construction characteristics is proposed (see Fig. 1).

Green walls can be subdivided in two main systems: green facades and living walls [22,39]. There is an evident distinction between green facades, where usually climbing plants grow along the wall covering it, and the most recent concepts of living walls, which include materials and technology to support a wider variety of plants, creating a uniform growth along the surface.

2.1. Green facades

Green facades are based on the application of climbing or hanging plants along the wall. Plants can grow upwards the vertical surface, like traditional examples, or grow downward the vertical surface, in case they are hanged at a certain height [39].

Green facades can be classified as direct or indirect. Direct green facades are the ones in which plants are attached directly to

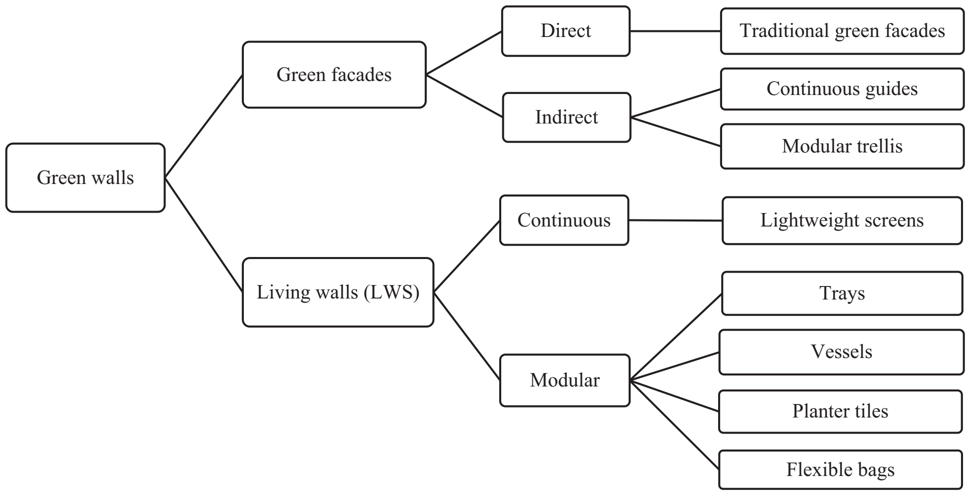

Fig. 1. Classification of green walls, according to their construction characteristics.

Fig. 2. Direct green facade, private house, Golegã, Portugal.

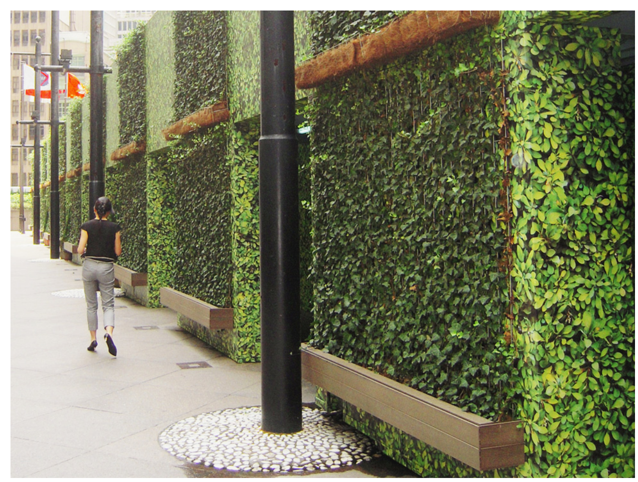

Fig. 3. Indirect green facade.

the wall. Indirect green facades include a supporting structure for vegetation.

Traditional green facades are considered a direct greening system, consisting on using self-clinging climbers, rooted directly in the ground (see Fig. 2).

New solutions of green facades are usually indirect greening systems, which include a vertical support structure for climbing plants development. In these examples plants can be rooted directly in the ground or in planters, and be guided to develop along the support structure.

Indirect greening systems include continuous and modular solutions. Continuous guides are based on a single support structure that directs the development of plants along the entire surface (see Fig. 3). Green facades with modular trellises are similar solutions, but result from the installation of several modular elements along the surface. The main differences are that modular trellises have vessels for plants rooting and an individual support structure for guiding plants development [46].

2.2. *Living walls*

Living walls are a quite recent area of innovation in the field of wall cladding. They emerged to allow the integration of green walls in high buildings. Living walls allow a rapid coverage of large surfaces and a more uniform growth along the vertical surface, reaching higher areas and adapting to all kinds of buildings. They also allow the integration of a wider variety of plant species.

Fig. 4. Continuous living wall system, Caixa Forum, Madrid, June 2013.

Living wall systems (LWS) can be classified as continuous or modular, according to their application method. Continuous LWS are based on the application of lightweight and permeable screens in which plants are inserted individually [47,48]. Modular LWS are elements with a specific dimension, which include the growing

Fig. 5. Modular living wall system, Natura Towers, Lisbon, August 2012.

media where plants can grow. Each element is supported by a complementary structure or fixed directly on the vertical surface.

Continuous LWS are also known as Vertical Gardens, a name given by the French botanist Patrick Blanc who reported his first "Vertical Garden", also designated as "Mur Vegetal" in 1994. Patrick Blanc spread the application of this type of LWS all around the world. His work is included in several buildings of the most famous architects (see Fig. 4).

In the category of living wall systems, the alternative to vertical gardens is the application of modular living wall systems (see Fig. 5), which is relatively new [39]. Modular LWS have differences in their composition, weight and assembly. They can be in the form of trays, vessels, planter tiles or flexible bags.

Trays are usually rigid containers, attachable to each other, that can hold the plants and substrate weight.

Vessels are an adaptation of the most common support for plants with the difference that they can be fastened to a vertical structure or be attached vertically to each other.

Planter tiles highlight the modular elements shape as elements of design for building's exterior or interior cladding. More than the creation of vegetation layer, they function as a modular cladding with insertions for plants.

Flexible bags include a growing media and lightweight materials that allow the application of vegetation in surfaces with different forms, as curved or sloped surfaces.

3. Systems requirements

Most recent developments in green walls are mainly focused in systems design and their elements (supporting elements, growing media, vegetation, irrigation and drainage) in order to achieve more efficient technical solutions and a better performance in all building phases (installation, maintenance and replacement).

The adaptability to more building types (e.g., commercial spaces, high rise buildings), construction methods (new or existing building walls) and types of surfaces (e.g., sloping surfaces, indoor partition walls and free-standing structures) [49,50] is also the concern in the evolution of green wall systems.

3.1. Supporting elements

Traditional or direct green facades usually have no support structure. They rely on the capacity of climbing plants to attach themselves to the vertical surface. However, when the vegetation fulfils full coverage can become too heavy and the risk of falling is increased.

Indirect green facades function as "double-skin facades", creating an air gap between the building surface and vegetation. The application of a support structure avoids vegetation to fall. These systems, either modular or continuous, anchor and hold the vegetation weight, contributing to increase the system resistance to environmental actions (e.g., wind, rain, snow). Most support structures for indirect green facades include continuous or modular guides, as cables, wires or trellis made of galvanized or stainless steel [51,52]. Steel structures and tensile cables (see Fig. 6) can be used to hold climbing plants with denser foliage and to support their weight. Grids and wire-nets have smaller intervals and can be used for slow growing plants support [53]. Some indirect green facades systems, mostly modular trellises, include pots filled with substrate and individual support structures, allowing the suspension of the elements along the wall at various heights. New forms of modular trellises include a curved grid to give the facade rhythm and three-dimensionality to the wall [51,52].

Living walls usually include a frame to hold the elements and a support for plants.

Continuous LWS are based on the installation of a frame fixed to the wall, forming a void space between the system and the surface. This frame holds the base panel and protects the wall from humidity. The base panel supports the next layers. It is covered with layers of permeable, flexible and root proof screens, stapled to the base. The external layer of screen is then cut to form pockets [47,48] for the introduction of plants individually (see Fig. 7).

Modular LWS can take several forms (e.g., trays, vessels, planter tiles or flexible bags) requiring a different structure.

Modular trays are usually composed of several interlocked parts, made of lightweight materials as plastic (e.g., polypropylene or polyethylene) or metal sheets (e.g., aluminum, galvanized steel or stainless steel) [54–59].To ensure the system continuity, each module normally includes an interlocking system on the sides to connect to each other. These modular elements may also contain a front cover forming a grid to prevent plants to fall (see Fig. 8).

Trays and vessels are usually fixed to a vertical and/or horizontal frame attached to the surface. The back surface can include hooks or mounting brackets [56,58] for their suspension in the frame profiles connected to the vertical surface.

Modular vessels allow the installation of several plants in each element along the same row. They are commonly made with polymeric materials and due to their form have a significant visual impact on the building surface.

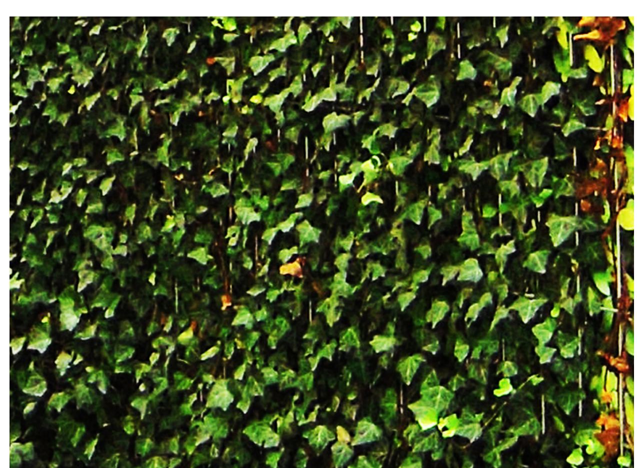

Fig. 6. Continuous green facade.

Fig. 7. Continuous living wall system.

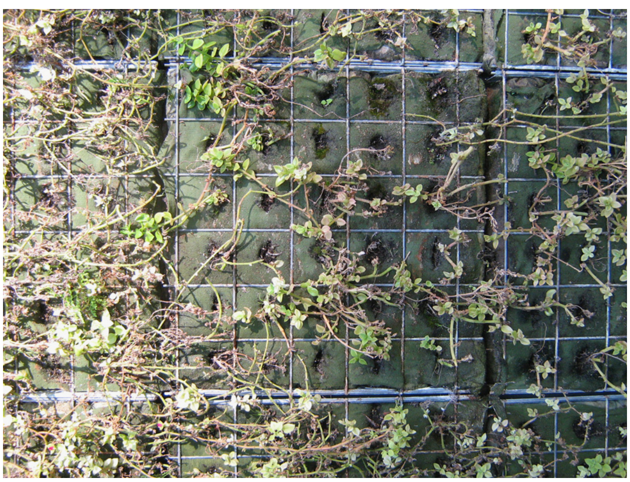

Fig. 8. Modular living wall system.

Planter tiles are connected to each other by juxtaposition. They often include a flat back fixed to the building surface and an area in which the plants are inserted individually. These solutions can be built in lightweight or porous materials like plastic or ceramics [60]. Depending on the system, tiles can be glued to the vertical surface [61] or be fixed with mechanical fastening [60].

Modular LWS can also take the form of elongate bags, filled with growing media, made of flexible polymeric materials which are cut to insert each plant [62].

3.2. Growing media

In the context of green facades only modular systems require the selection of a growing media, which must be lightweight, considering that each element will be suspended, and adapted to the selected plant species and environmental conditions.

In the field of living walls, continuous LWS also do not have substrate. As mentioned before, these systems use lightweight absorbent screens where plants are inserted in pockets. Continuous LWS are commonly based on a hydroponic method, requiring a permanent supply of water and nutrients due to the lack of substrate. Hydroponic systems allow the growth of plants without soil, using screens constantly moist by the irrigation system. The lack of soil is compensated by providing the necessary nutrients for plants development through irrigation water.

Modular LWS are commonly filled with a growing media where roots can proliferate, made of organic and inorganic compounds [49,58,59] or include a layer of inorganic substrate, usually foam, to reduce its weight. Most modular LWS include a growing media based on a mixture of light substrate with a granular material, expanded or porous (e.g., mineral granules with medium to fine particles, coconut fibbers or recycled fabric) in order to obtain a good water retention capacity [56,63]. The substrate may be improved with nutrients for plants growth (e.g., mixture of organic and inorganic fertilizers, metal chelates, minerals, nutrients and hormones for plants or other additives) [58]. Some modular LWS indicate the insertion of growing media into geotextile bags to prevent its detachment. These bags can occupy the entire module and allow the insertion of several plants [56], or cover the growing media of each plant individually [54,57]. Alternatively, each plant can include an individual front cover to avoid the growing media to fall [58].

3.3. Vegetation

The appropriate vegetation depends on climatic conditions, the building characteristics and the surrounding conditions, in which the green wall is inserted. The analyzed systems show some concerns with vegetation longevity.

Climbing plants are considered a cheap solution of vertical greening. These plant species can contain two main types of foliage, evergreen or deciduous. Evergreen plants maintain their leaves all year and deciduous plants lose their leaves during the fall, having a strong visual change along the year.

Climbing plants can be self-supporting, attaching themselves to the vertical surface (e.g., root climbers and adhesive-suckers) or be supported by a structure [52] were they can hold (e.g., twining vines, leaf–stem climbers, leaf climbers and scrambling plants). They were traditionally used in Germany and France to cover the exterior walls of small buildings. In warm-summer climates vines were commonly installed in pergolas to shade buildings envelope [39]. It is also important to consider that climbing plants have growing limitations. Some species achieve 5 or 6 m, others 10 m and some 25 m high [39] and take about 3–5 years to achieve full coverage [53].

A study performed in the Mediterranean Continental climate compared the development of several climbing plants, perennials (*Hereda helix, Lonicera japonica*) and deciduous (*Parthenocissus quinquefolia, Clematis sp*), according to the achieved foliage density after one year of development. It revealed that *Parthenocissus quinquefolia*, also known as Virginia creeper, provided greater density of foliage, but none of the selected species could cover the entire surface after one year. Some species also reveal difficulties to adapt to the climatic conditions, with high temperature variations along the year and low rainfall, as *Clematis* which was affected by summer conditions [30].

Living wall systems allow the development of new aesthetical concepts of green walls, based on the creation of artistic solutions with plant species, exploring the use of patterns, variations in color, texture, foliage forms and density, vitality and growth. These solutions brought a wider variety of plant species to green walls, allowing the integration of shrubs, grasses and several perennials as long as their watering and nutrient needs are taken into account.

Hydroponic systems make possible the growth of a wider variety of plants, in different states of development: grown plants, cuttings or seeds [64]. In these cases vegetation is selected according to the desired aesthetic effect [56,65], requiring the appropriate irrigation and nutrients for an adequate plant development. Therefore, it is important to analyze plants development, color, blooming, foliage and the global plant composition, according to the artistic intentions to a certain building (e.g., building framing in the urban context, advertisement of a particular company, or marking distinction of an certain building or interior space).

However, in order to fulfill sustainability goals, vegetation must have low irrigation needs (e.g., use of native plants), be adapted to local conditions of exposure (e.g., sun, semi-shade or shade) and weather conditions (e.g., wind, rainfall, heat, drought and frost).

Recent examples of modular LWS include the option of using *succulent* carpets in green walls instead of perennials and shrubs. The use of drought tolerant plant species as succulents [1] reduces the needs of irrigation. These plant species have also low maintenance and contribute to the minimization of the system weight. However, succulent carpets acquire the appearance of a flat vegetated surface, which can be interesting in small walls. In larger surfaces the use of perennials and shrubs allows the creation of more ornamented landscapes due to the variety of colors and textures that these plants can include. A Japanese system [62] also exemplifies the application of certain shrubs which can be used in inclined surfaces (e.g., *Juniperus chinensis*, *Juniperus conferta*, *Euonymus Fortunei*, *Cotoneaster*, *Cotoneaster Horizontal, Vitex rotundifolia*).

Green walls have a particular potential for urban agriculture, particularly in cities where there is lack of land for cultivation, reducing the environmental impact related to food production and distribution [53]. New concepts of green walls consider the integration of vegetables and aromatic herbs in green facades, continuous LWS [48] or modular LWS (Fig. 9), as planters [60] or vessels [61], increasing the functional potential of the system itself to building users.

3.4. Drainage

Excess fluid drainage in green walls takes place by gravity.

Continuous and modular LWS use geotextiles that encourage drainage along the permeable membrane while preventing roots proliferation.

Modular trays take advantage of the overlap of modules and materials to improve drainage and water excess reuse to the modules below. For a better drainage the bottom of a modular systems can be concave, inclined, perforated or be made in a porous or absorbent material [55]. Other examples as vessels mention the use of a filter material applied at the bottom of the module [61] (e.g., inoculated sand or other mean to purify rainwater, remove toxins and heavy metals) or a granular inert filler [65] (e.g., expanded clay, expanded slate, gravel) which promotes the drainage and development of roots. Some examples of modular systems also mention the insertion of grooves or holes on the sides and back face of modules, for a better aeration and removal of excess moisture contained in the substrate [56,59].

Fig. 9. Modular living wall with edible plants [66].

3.5. Irrigation

The irrigation needs depend on the type of system, plants used and climatic conditions.

Modular green facades and LWS require an irrigation system in order to provide the necessary water to plants development. The irrigation water can be enriched with nutrients, fertilizers, minerals, phosphates, amino acids or hydroponic materials to improve the vegetation development and vivacity.

The water supply of LWS is made through the installation of a continuous irrigation tube located at the top. Continuous LWS have an irrigation system installed at the structure top connected to the central irrigation system. In the case of continuous LWS the permeable screen allows the uniform distribution of water and nutrients along the surface.

Some modular LWS in the form of trays include a recess in the top face of the module to insert the irrigation tube. The trays include several holes in the recess for watering the growing media by gravity [54,55,57,58]. Drainage holes located in trays bottom are used to allow excess water to irrigate the modules underneath.

The irrigation tubes and connectors can be produced in several materials (e.g., rubber, plastics, piping thermoplastic, silicone and irrigation hose) containing different outputs (e.g., drip, sprinkler, holes, pipe) with distribution and intensity adapted to the plants irrigation needs. The irrigation system can also include a filtration system to prevent clogging.

Some LWS also mention strategies for minimizing the consumption of treated water. There are strategies like rainwater recovery [56] from the building roofs, reuse of the fluid collected in the drainage system [67] and monitoring water supply needs [55], through the installation of sensors [47,48] that control the collecting water tank level, the irrigation time and weather conditions (e.g., quantity of rainfall, humidity, temperature, atmospheric pressure).

Other LWS, either modular [60,68] or continuous [47,48], also refer the installation of a gutter in the system base, recovering excess water storing it and reintroducing it into the irrigation system.

Another strategy consists in the application of sensors in the growing media for nutrients needs quantification. This can be important to minimize nutrients consumption and match the plants needs.

3.6. Installation and maintenance

Green facades, including climbing species, are more cost-effective during the installation process but have limitations in plants diversity. When there is the necessity of plants replacement, these systems show difficulties in ensuring vegetation continuity. During plants growth, some climbing plants also require guidance to ensure that they cover the entire surface. It is also important to refer that some climbing plants can damage buildings surface, destroying it with their roots and entering in voids or cracks.

Modular trellises have advantages when compared to continuous guides on the installation and maintenance processes. The installation of plants at several heights decreases significantly the impact of the disperse growth of climbing plants along the surface and enables the substitution of unsuccessful plants.

A crescent number of modular LWS emerge in the market to minimize installation, maintenance and replacement problems.

Some modular systems enable to disassemble each module individually [59] or include a removable front cover [57] for wall maintenance or vegetation replacement. Some modular elements can also be nested into each other in order to simplify the transportation and application processes.

When comparing continuous LWS to modular LWS, continuous LWS enable the creation of vegetated surfaces with a wider variety of plant species, and can be lighter, has a density of around thirty plants per square meter and less than 30 kg/m^2 [64]. However, continuous LWS are commonly hydroponic systems, requiring a permanent supply of water and nutrients, which constitute a sustainability disadvantage and result in higher maintenance costs due to higher irrigation needs.

In fact each green wall system has its own characteristics, with advantages and disadvantages depending on their aesthetic potential, cost and maintenance needs (Table 1). The selection of the most adequate system is directly related to the building characteristics (e.g., orientation, accessibility, height) and climatic conditions (e.g., sun, shade and wind exposure, rainfall). This is why it is important to understand their differences in composition and their main characteristics (Table 2).

3.7. Environmental performance and costs

To better understand if green wall systems may be considered sustainable solutions, several studies were conducted by researchers to compare the environmental performance of different green walls systems during their entire lifecycle.

Direct green facades are a more sustainable [69] and economic solution [45]. These systems have a small environmental burden considering that they have no materials involved and have low maintenance needs.

When analyzing the life cycle of some LWS their sustainability may be questioned. Differences in the type of materials used, their durability, recycling potential, vegetation durability and water consumption can have a significant impact on the total environmental burden [44,70]. As shown by Ottelé et al. the integration of stainless steel as supporting system can have an impact 10 times higher than using other recycled materials (e.g., HDPE, hard wood with FSC certificate or coated steel) [44]. Another important matter is materials durability. Several materials as PVC and others have a limited durability requiring its replacement more than once during buildings life expectancy.

Nevertheless, green wall systems frequently use materials with high environmental impact. Recent studies proof that some systems can have a reduced environmental burden by contributing to the thermal resistance of the wall, leading to a reduction on energy demand for heating and cooling [44].

The cost of green wall systems can also be a variable with significant impact on the selection process. LWS are more expensive when compared to direct and indirect green facades. Direct and indirect green facades can cost less than 75 €/m^2 [45].

Table 1
Comparison of green wall systems advantages and disadvantages.

System	Category	Sub-category	Advantages	Disadvantages
Green facades	Direct greening	Traditional green facades	No materials involved (support, growing media, irrigation) [71] Low environmental burden [44] Low cost [45]	Limited plant selection/climate adaptability Spontaneous vegetation development [45] Slow surface coverage [53] Scattered growth along the surface [23] Surface deterioration [23,39]/plants detachment Maintenance problems [33,45]
	Indirect greening	Continuous guides	Vegetation development guidance [53] Low water consumption [71]	Limited plant selection/climate adaptability [30,71] Slow surface coverage [53] Scattered growth along the surface [23,26] High environmental burden of some materials [44,71]
		Modular trellis	Lightweight support [23] Vegetation development guidance [51] Controlled irrigation/drainage [51] Easiness to assemble and disassemble for maintenance [30] Plants replacement	Limited plant selection/climate adaptability [46] High environmental burden of some materials High installation cost [45]
Living walls	Continuous systems	Felt pockets vertical gardens	Uniform growth [71] Flexible and lightweight [47,48] Increased variety of plants/aesthetic potential [45,64,71] Uniform water and nutrients distribution [48]	Complex implementation [23] High water and nutrients consumption [71] Frequent maintenance [44] Limited space for root development [48] High installation cost [45]
	Modular systems	Trays	Easily disassembled for maintenance [57,59] Increased variety of plants/aesthetic potential [45,64,71] Controlled irrigation/drainage [55,67]	Complex implementation [23] Heavier solutions Surface forms limited to trays dimensions High environmental burden of some materials [44,71] High installation cost [45]
		Planter tiles	Increased variety of plants/aesthetic potential [45] Attractive design of modules [60]	Complex implementation [23] Limited space for root development [60] Surface forms limited to tiles dimensions [60] High installation cost
		Flexible bags	Adaptable to sloped surfaces [62] Increased variety of plants/aesthetic potential [45]	Complex implementation [23] Heavier solutions due to growing media/limited to buildings maximum load [62] High installation cost

Table 2
Summary of green wall systems composition.

System requirements	Green facades	Continuous LWS	Modular LWS
Support	Cables, ropes, nets, trellis in stainless steel, galvanized steel, wood, plastic, glass fiber [51–53,67]	Geotextile felts [47,48,64]	Galvanized steel, stainless steel, lightweight and/or flexible polymers, ceramics [54–62]
Growing media	Ground soil or vessels filled with substrate [39,51]	–	Substrate mixture including organic and/or inorganic compounds [45,47,48,56,58,63,64]
Vegetation	Climbing plants (evergreen or deciduous) [24,30,33,39,42,45,52]	Shrubs, grasses and perennials [6,64]	Shrubs, grasses, perennials and succulent plants [6,31,45]
Drainage	Vessels with inferior holes [51]	–	Lateral and inferior holes [54–59,63]
Irrigation	Drip line inside vessels [51,60]	Drip line on the top of the wall [47,48,64]	Drip line on top of each module [54–59,63]

Modular green facades have variable costs depending on the materials used, for example a system using galvanized steel can be 4–8 times more expensive than a system using HDPE. In the case of LWS the costs are also very dependent on the materials used and the system complexity, reaching to a cost of 1200 €/m^2 [45]. Indeed the cost depends also on the application process (considering the surface dimension and accessibility) and maintenance needs (e.g., irrigation, nutrients, plants replacement).

Nevertheless, improving the performance evaluation of recent green wall systems can lead to an increase of their application in buildings and therefore result in a reduction on their cost.

Importantly, the decision of which green wall system is more appropriate to a certain project must depend not only on the construction and climatic restrictions but also on the environmental impact of its components (e.g., energy or water used and materials recyclability) and associated costs during its entire lifecycle.

4. Conclusions

The analysis of the most relevant systems in the field of green wall systems demonstrates that there is a significant evolution in this field. Some examples either modular or continuous focus on its lightness, through the application of geotextile and polymeric materials. This can be very useful with regard to the application of these systems in buildings rehabilitation [71].

Continuous solutions are often lighter than modular systems. But most recent developments of green wall systems design are mostly focused on modular systems, offering advantages of installation, allowing a rapid coverage of the entire surface, and simplifying their maintenance, enabling the disassembly and replacement of each element.

In the field of green wall characteristics, the main concerns are to find new strategies for a better performance and durability through the integration of water retention materials, drainage means and simpler assembly and maintenance processes.

Systems adaptability is still a field of development. New solutions must focus not only in the application in new buildings but also in the rehabilitation of existing buildings, introducing greening in historical areas [17]. Most systems are designed to be applied in the vertical plan, allowing, in some cases, their application in inclined plans with some restrictions. Therefore, green walls must evolve and adapt to different surface forms and inclinations (e.g., curved, vertical or horizontal surfaces), with the convenient adaptations [72].

Considering the analysis of different types of green wall systems, it can be understood that innovation is mostly centered in the improvement of their design to achieve a better performance, during the installation, usage or maintenance processes [73].

Yet, green walls must evolve to become more sustainable solutions [74], through the use of materials with less incorporated energy and CO_2 emissions and the application of climate adapted plant species with less irrigation needs [73]. Some examples already show sustainability concerns by using natural or recycled materials and native plants, integrating water recovery systems and sensors for water and nutrients minimization.

In fact, continuing to evaluate the contribution of recent green wall systems to improve buildings performance and comparing the environmental impact of these systems with other construction solutions can lead to an increase of their application in buildings and therefore result in a reduction on these systems cost.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.07.203.

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