Green Wall systems: where do we stand?

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Abstract. In the last few years, the increase of impervious surfaces, due to ongoing urbanization and climate change led several environmental impacts such as: urban heat island effect, air pollution, urban flooding, deterioration of water discharged in the receiving water bodies, and so on. In this context, a sustainable strategy is required, and an innovative solution can be found in the implementation of low impact development (LID) systems as green walls. These sustainable solutions, by reintroducing vegetation in urban area, can partially restore the pre-urbanization situation and mitigate these drastic environmental impacts. To investigate the state of art of these techniques, a deeper overview on the green wall systems was carried out. This analysis was finalized to evaluate the current developed systems in terms of classification, components and benefits in order to establish where do we stand in terms of evolution of these systems and where we are going in terms of new trends and possible future directions.

Keywords: Climate Change, Review, Vertical Greening System, Green Facades, Living Wall

1. Introduction

The combined effect of uncontrolled urbanization and climate change is one of the most challenging problems of our time [1,2]. The drastically increase of urban heat island effect, air and water pollution, urban flooding, loss of ecosystems as well as human health and well-being can be considered the main environmental issues at global scale produced by these challenges. Only an innovative, sustainable, and ecologically based approach can meet all these impacts, which even if are different from each other are strongly correlated.

Therefore, there is a growing attention of the governments to promote actions to develop sustainable cities and societies [3]. In this regard, a promising strategy is the implementation of nature-based solutions, also known as Low Impact Development systems (LID) or Green Infrastructures (GI), which reintroducing vegetation in areas highly urbanized, can restore the pre-development conditions and mitigate the impacts due to climate change and urbanization, providing several benefits at multiple scale [4-7].

Among these systems, green wall techniques, generally mentioned also as vertical greening/greenery systems, vertical garden, bio-walls, and so on, [8] can be considered as a sustainable strategy, that by using spaces otherwise unused, able to obtain beneficial effects from the building to the urban scale. Specifically, at building scale, by optimizing the benefits of plants species, they can be considered passive design solutions which improve thermal comfort both in winter and summer, thereby reducing
energy demand for heating and cooling [9,10]. In addition, the implementation of a green wall increases the value of the real estate and allow sound insulation; while at urban scale, these systems can enhance air quality, urban biodiversity, mitigate urban heat island effect [11,12]. They represent also a control source of stormwater management at urban catchment scale [13]. Moreover, from a social point of view, the implementation of vegetation on facades improve cities image and wellbeing, favouring the fruition of them [14].

Given their effectiveness from many points of view, several studies have been carried on these ecologically solutions. In this regard, here we present an overview on the papers published on green wall systems in order to: analyze the current state of art in terms of developed systems (components, materials and features), design and construction methods, systems benefits; evaluate the main differences, and establish where do we stand in terms of evolution of these techniques and where we are going in terms of new trends and possible future directions.

2. Green Wall systems: types and components

The green wall system represents one of the low impact development (LID) solutions able to increase the green spaces in urban area, aiming at enhancing the aesthetic value of the building and leading several benefits in terms of reduction of the environmental impacts caused by urbanization and climate change.

Since with the term “green wall system”, we refer to each form of vegetation for facades, the first applications can be found 2500 years ago in the hanging Gardens of Babylon; similar examples were also in the Roman Empire. Many applications occurred over the centuries, until the 19th century, when these techniques were used in several European and North America cities, as ornamental elements and for thermal purposes [8,15,16].

Nowadays, with “green wall” we refer to a vegetative system which is, generally, developed along the façade of a building, consisting of different components, and it can be directly attached on the wall or supported by a structure [8,16].

To better identify the characteristics of the different green wall systems typologies, it is necessary to introduce the general functional elements of this technique, consisting of: (i) supporting elements; (ii) growing media; (iii) vegetation; (iv) drainage; and (v) irrigation. Based on the features of these elements and on the presence or absence of some of these, the green wall systems can be subdivided into two macro-categories: Green Facades (hereafter named GFs) (Fig. 1) and Living Walls (hereafter named LWs) (Fig.2) [8].

The Green Facades (GFs) are characterized by a low systemic technology, few constituent elements, and a limited level of integration between plants and walls. They are light, easy to install and, generally, aimed at supporting the natural development of plants, mainly climbing plants, that can have evergreen foliage or deciduous, and reach until 25 m of height, taking, however, some years for the full coverage of the wall [8].

In addition, as it is possible to observe in Figure 1, in function of the presence or absence of the supporting structure, the green facades can be differentiated into direct GFs and indirect GFs systems. In the first case the plants are directly attached to the wall; while the indirect GFs present a structural support for the growth of vegetation, generally consisting of continuous or modular guides (tensile cables, stainless steel, grids, etc.). This support structure leads several benefits: to prevent the falling of vegetation, to create an air gap between the surface of the building and the vegetation, to increase the system resistance to the environmental actions as rain, wind, snow, and so on. Moreover, for both systems, in case of very tall buildings or lack space at the base of the building, it is possible to use special boxes (Fig. 1b and 1d), placed at intermediate heights [8,15,16].
Figure 1. Different types of Green Facades: (a) Direct Green Facade with vegetation planted into the soil; (b) Direct Green Facade with plants rooted in the box; (c) Indirect Green Facade with vegetation planted into the soil; (d) Indirect Green Facades with plants rooted in the box.

Figure 2. Different types of Living Walls: (a) Continuous Living Wall; (b) Modular Living Wall.

The Living Walls (LWs), allowing the rapid coverage by vegetation of high building, represent a more recent innovation than the green facades. These types of green wall can use a wide variety of plants species (grasses, perennial plants, shrub, succulent, and so on), selected according to the climate condition, the drought tolerance, the root development, and specifically combined to achieve aesthetic effects [8].

Based on their application method, the LW systems can be continuous (Fig. 2a) or modular (Fig. 2b). More in detail, the continuous LWs do not require a substrate of soil, but the plants grow in lightweight and absorbent screens, as a fabric layer (i.e. felt), cut to form pockets. This layer is connected to different layers (permeable, flexible and root proof screens), supported by a base panel, directly attached to a
supporting structure, consisting of a frame indirectly fixed to the wall. These types of systems are mainly based on hydroponic technique [8,16,17]. The water supply is generally guaranteed by an irrigation system installed at the top of the structure, while the permeable layer ensures the uniform distribution of water and nutrients [8]. On the other hand, the modular LWs are characterized by pre-vegetated panels with specific supporting elements (vessels, trays, flexible bags, planter tiles) in which the plants grow. The growing media consists in an organic and/or inorganic substrate, which present a good retention capacity, and where the roots can proliferate. The irrigation system, according to the configuration of the supporting elements, is generally installed between the panels, and the water is drained through the panels for the entire facade and collected on the bottom [8,15].

Due to its specific feature the Modular LWs provide greater seeding depth than the continuous ones, and, allow easy maintenance in terms of replacing plant species [11,18].

By comparing the two main categories (GFs and LWs), in terms of installations cost, it is detected that although the LWs require much more materials than the GFs and, therefore, the costs are higher, they offer several benefits during the maintenance process. In fact, in case of unexpected problems, the LWs panels can be easily replaced or it is possible to provide a more rapid renewal of vegetation [8,19-22]. While, the direct GFs present the advantage to not require a supporting structure, but the disadvantage to employ a long period to cover the entire wall. The use of a supporting structure offers the benefits to have a space between the system and the wall, which could be used for insulation or maintenance purposes [8,23].

3. Green Wall Benefits: an overview

Green wall systems represent sustainable solutions to restore the environmental quality of urban areas by re-introducing vegetation. Due to their features, these systems provide several benefits at multiple scale.

Thus, in agreement with the European energy saving directions, that promote a rational and sustainable development starting by the building sector [24], several studies have proved the potential benefits of the green wall systems in terms of reduction of internal building temperatures and energy consumption, and mitigation of urban heat island effect [25]. In fact, since the plants function as a solar filter and prevent the adsorption of heat radiation, the use of greening systems produces a strong effect on the thermal performance of buildings and on the urban environment [19].

In this regard, Eumorfopoulou and Kontoleon [26] have evaluated the thermal analysis of two equal building floors (one with bare surface and one plant-covered surface). The findings have shown the importance of the contribution on the thermal behaviour of plant-covered wall sections in densely populated urban areas in Mediterranean region during the cooling period.

The same authors, the year after, presented another work on how the wall orientation, the wall plant foliage percentage, and the type of wall configuration can affect the thermal behaviour of typical building located in the northern Greek region during the summer period [20]. The results, obtained by using a validated thermal-network model, were: a superior thermal comfort conditions within the building zone that included a plant-covered wall; an increase of thermal benefits when there was more percentage of plant foliage; benefits in terms of energy conservation of a plant-covered wall, which allowed to improve the microclimate around the built environment by neutralizing the solar impact.

During the same year, Cheng et al. [27] used an experimental approach to assess the effect of vegetation on the thermal performance of a vertical greening system, obtaining that the vegetated cladding reduced interior temperatures and delayed the transfer of solar heat. Therefore, the implementation of the green system decreased power consumption in air-conditioning compared with a building with bare concrete.

While in another work, Wong et al. [9] showed the potential thermal benefits of eight vertical greenery systems, located in HortPark, to reduce the surface temperature of buildings facades in the tropical climate, and decrease the cooling load and energy cost.
In 2011, Jim and He [28] evaluated the thermodynamic transmission process of the vertical greenery ecosystem, by designing a field experiment and developing a thermodynamics transmission model. The results showed that: the green wall radiation transmission was strongly correlated with canopy transmittance and reflectance; the thermal shielding effectiveness depended on the orientation; due to the presence of the vertical greenery ecosystem and, therefore, its more intensive evapotranspiration effect, the south wall could transfer much more heat flux.

The same year, Perini et al. [19] analyzed the possible reduction of the wind velocity and (air and surface) temperature by three different green wall systems in the Netherlands: (1) direct façade greening (Delft); (2) Indirect façade greening system (Rotterdam); Living wall system (Benthuizen). The findings showed not difference in the air temperature and wind profiles starting from 1 m in front of the façades until inside the foliage. Moreover, the investigated systems could be considered effective natural sunscreens; a low wind velocity was monitored inside the air cavity of the Living Wall and inside the foliage of the direct and indirect systems. In addition, due the reduction of wind velocity, the exterior surface resistance could be equalized to the interior one and, therefore, affect the total thermal resistance with results in terms of energy savings.

Mazzali et al. [29] monitored three Living Wall field tests in different climate context located in Mediterranean temperate region (at latitudes corresponding to Northern and Central Italy) to investigate the potential effects of the energy behaviour on building envelopes. The analysis revealed a temperature difference between the bare wall and the covered wall ranging between a minimum of 12 °C (for the living wall located in Lonigo) and a maximum of 20 °C (for the living wall located in Pisa), during sunny days. In addition, the analysis on the heat flux showed how these systems can significantly contribute to cooling energy reduction.

Coma et al. [30], by comparing the thermal performance of two experimental vertical greenery systems (a double-skin green facade with deciduous creeper plants and a designed green wall with evergreen species), obtained a high potential energy savings for green wall (58.9%) and double-skin green facade (33.8%) in comparison to a reference system during the cooling season, and no extra energy consumption for evergreen system during heating periods.

In the Jubilee Campus of University of Nottingham, by an experimental and numerical investigation on the thermal regulation feature of green wall systems located at the University, Cuce [25] obtained an average of 2.5°C temperature reduction in internal wall for green walls with around 10 cm thickness climbing vegetation of Hedera helix

To investigate the potential benefits of green walls as passive tool for energy saving, Perez et al. [31] investigated a double-skin green facade implemented in an experimental site in Mediterranean continental climate. The experimental findings showed the high potential of the green system as a passive system in comparison to the reference conventional site, obtaining an energy saving up to 34% with a leaf area index of 3.5-4. In addition, the results showed that, since the shadow effect of green facades on the East and West orientations was representative, this should be considered as well as that one of South orientation.

Another study, carried out by Tudiwer and Korjenic [32], analyzed the influence of two greened façades on the thermal resistance of the walls, by developing a method to evaluate the U-value at greened facades. The results showed: a lower temperature on the surface without vegetation in the winter, even for south orientation; the greening reduced the fluctuation rate of the surface temperature and the heat flux; the difference of the thermal between vegetated and not vegetated sections in winter ranged between 0.31 m²K/W and 0.68 m²K/W.

In Mediterranean climate, Perini et al. [10] evaluated the cooling potential during the summer season of a vertical greening system built in Genoa (Italy). The findings showed that a green layer can decrease outdoor and surface temperature, improving thermal comfort and the building surfaces heating and, thus contributing also to urban heat island mitigation. In addition, the presence of vertical greening system allowed a reduction of cooling demand of 26% during summer.

In another study, Galagoda et al. [33] quantified the thermal performance, the relative humidity and the CO2 concentration for three types of green infrastructures: living walls, indirect green façades and
direct green façades located in Colombo metropolitan in Sri Lanka. Comparing the results with the bare wall, they obtained a maximum temperature reduction of 8.0 °C - 0.28 °C for the living wall, 7.86 °C - 1.34 °C for the indirect green facades, and 6.64 °C - 1.34 °C for the direct green facades. In addition, the study showed an averaged relative humidity increase of 1.6%–1.81% and a CO2 reduction of 0.63% near green walls. Then, the authors demonstrated the capability of these systems on micro climatic changes and human thermal comfort. The green walls were able to reduce 2.4 °C at indoors compared to bare wall building; an energy saving of 10.97 MW was obtained; and, finally, a positive perception of 79% of people, a thermal comfort by 58% of inhabitants, a visually comfort of 89.5%, a satisfied about the light penetration level of the vertical greening systems of 61% occupants, were reached.

As it was possible observed, the benefits in terms of energy saving (for reduction of air conditioning demand) is strongly correlated to the economic sustainability of the green wall system. In this regard, Rosasco and Perini [34] carried out a Cost-Benefits Analysis on the vertical greening system, installed at Genoa (Italy), in order to evaluate its economic sustainability. The findings revealed that the system can be economically sustainable when a tax reduction on installation costs is considered. In addition, by a sensitivity analysis they found how the optimal choice of the materials and technological solutions during the design phase is relevant to reduce the installation and maintenance costs.

In addition, from the overview carried out, it is emerged that the vertical greenery system can be also considered a Key element to mitigate the noise pollution. In this regard, Wong et al. [35] evaluated the acoustics impacts of eight different vertical greenery systems installed in HortPark, Singapore on the on the insertion loss of building walls. Furthermore, they determined the sound absorption coefficient of a vertical greenery system developed in the reverberation chamber of National University of Singapore. The results of first part of the study showed a higher attenuation at low to middle frequencies due to the absorbing effect of substrate; while at higher frequencies, a smaller attenuation was observed due to scattering from vegetation. During the second part of the study, they determined the sound absorption coefficient which resulted one of the highest values compared with other materials and obtained that this coefficient increased with the frequencies and with greater greenery coverage.

To evaluate the benefits of these systems in terms of mitigation of impacts due to climate change, another environmental aspect was considered. The green walls systems, like green roofs or rain gardens, are low impact development solution that can be considered sustainable tools able to restore the pre-urbanization hydrological natural cycle and, thus mitigate urban flooding risk. In literature, the benefits of these solutions in terms of runoff mitigation were not widely investigated as well as the other LID solutions (green roof or rain garden). In this regard, Lau and Mah [13] studied the green wall hydrological effectiveness, by developing a USEPA SWMM model, that considers the green wall system as a portion of urban drainage system. More in detail, the study is based on a modelling implementation of a modular green wall system on the commercial building in Central City, Kota Samarahan. They carried out four simulation models, characterized of different conditions (soil texture classes: sand, loamy sand, sandy loam and loam) and precipitation input. The findings confirmed that green wall systems can be effectively considered for reducing surface runoff.

Moreover, to better investigate the environmental impacts of green wall techniques, a comparative life cycle analysis (LCA) was carried out by Ottelé et al. [17] for Mediterranean and Temperate climate condition. They considered different facades: a conventional bare wall (brick), a direct green façade, an indirect green façade, a living wall system based on planter boxes and another living wall system based on felt layers. The results revealed that, due to the reduction in energy demand for heating, even if additional resources needed, the direct greening system, the indirect greening system (with hard wood, coated steel or HDPE as supporting system) and the living wall system based on planter boxes represented a good environmentally choice.
Finally, starting by the concept of “reconciliation ecology”, Francis e Lorimer [12] evaluated the reconciliation potential of living roofs and walls, by observing that: the successful implementation of these ecological engineering techniques is strongly related to the participation of urban citizens; and these systems are important solutions to enhance urban biodiversity.

In conclusion, based on the analysis carried out, the green wall system can contribute significant environmental, social and economic benefits for the built environment. From the overview, it is highlighted the difficulty to compare studies which consider different construction system, climate, plants species, and other parameters (as orientation, thickness, etc.). However, the analysis allowed to evaluate the scientific gap on the green wall system in terms of the performance evaluations and investigate the new trends and future directions.

4. New trends and future directions in green wall technology

In the last few years, new several applications encouraged the growth of green wall techniques as tool for energy saving and this was deeper demonstrated in the previous overview.

However, as green infrastructures, these systems, like green roofs or rain gardens, can be valuable engineering solutions to reduce the stormwater discharged into the drainage systems, mitigating thus the urban flooding risk. But, from the literature review, it is emerged that green walls were little investigated as elements able to reduce the runoff in urban environment. For example, Studies on the laboratory analysis of the retention capacity of green walls soil substrates, were not find, as well as experimental and numerical investigations on the hydraulic efficiency of these systems at urban scale. Based on this background, future scientific trends could focus on the investigation of the hydraulic performance of green walls both by developing experimental lab analysis and modelling the flow inside the porous media and evaluating the hydrological efficiency of these systems from the building scale to the catchment. In addition, another innovative element, in the field of water management, could be the optimal integration of a green wall system with a rainwater harvesting system. The rainwater harvesting system could provide the irrigation to the green wall, by reusing the water discharged from the system itself. In addition, given the potential of vegetation, these systems could be further investigated as tool to mitigate water pollution.

Finally, a further green wall optimization at multiple scales could be achieved, by developing smart façade systems, i.e. façades that dynamically respond to the demands and conditions received by the external environment. In this direction, for example it could be possible to optimize the green wall irrigation, monitoring the soil humidity and the inside and outside building temperature.

Therefore, it is expected that the research on green walls will increase, by focusing the attention also on the benefits and implications not still deeper investigated.

In this regard, the study, here presented, is a part of the analysis carried out during the project “Innovative Building Envelope through Smart Technology (I-Best)”, developing at University of Calabria (Italy) in Mediterranean climate. This project involves, as one of the objectives, the experimental analysis, the modelling development and the full scale implementation of an innovative modular green wall system, aimed at decreasing urban flooding risk, achieving water saving, reducing water pollution, enhancing biodiversity, and mitigating other environmental impacts due to climate change.

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