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Green envelopes classification: the comparative analysis of efficient factors on the thermal and energy performance of green envelopes

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Abstract

This paper classifies green envelopes as green roofs and green walls according to effective factors, which were derived from literature to compare the green envelopes' thermal and energy performance in a more effective way. For this purpose, an extensive literature review was carried out by searching keywords in databases and studying related journal papers and articles. The research method for this study was bibliographic and logical reasoning. The paper proposes five classification factors: contextual factors, greenery factors, scale factors and surface and integration factors. It also demonstrates the influence of physical and geometrical properties of plants and their supporting structures on the thermal performance of green envelopes. The paper argues that climatic conditions also have an important role on the thermal behavior of green envelopes and it determines the types of greenery integration into building envelopes.

Keywords: *Green roof, Green wall, Thermal function, Energy performance, Living envelope.*

1. Introduction

Green envelopes in this paper are defined as any surface of the building envelope with greenery. Usually these green surfaces are known as green roofs and green walls. Using greenery on building exterior surfaces dates back to a long time ago. From a certain point of view, it was foliage and tree branches that made the first houses for human beings [1]. The hanging gardens of Babylon, which date back to 2000 to 3000 years ago, were one of the most famous examples of using greenery on building surfaces [2]. Another example is traditional Scandinavian sod roofs with their low slope and good thermal insulation, which were common in many rural areas of Scandinavia [3]. Also, from 3rd century BC until 17th century AD, the Romans used trellises for growing grape on villa walls [4].

Modern greenery systems on roofs can be divided into the two main types of extensive and intensive systems [5-7]. Intensive and extensive green roofs have the same constituting layers: from top to bottom: (1) vegetation, (2) substrate, (3) filter membrane, (4) drainage layer, and (5) root resistance layer. Plants cultivated on green roofs range from native plants and grasses to drought tolerant types such as Sedum and Delosperma species, which belong to the cactus family of plants [8-13] [Fig. 1].

Intensive green roofs are frequently designed as public places and include mostly herbal perennial plants, trees, shrubs, and hardscapes similar to landscaping found at the ground level. They generally require substrate depths greater than 20 cm to 120 cm and 'intense' maintenance. In comparison, extensive green roofs are lighter and cheaper with lower capital cost and need less maintenance. The substrate depth for extensive roofs is between 5 cm and 15 cm, which can grow slow growing plants with low height and weight such as grass, herbs or drought-tolerant sedum [5, 14-20].

Green walls or green vertical systems can also be divided into two different categories according to the level of maintenance and variety of plant types that can be used in them. Intensive green walls need more care and use more types of plants [21] [22]. However, green walls are usually classified into green façades and living walls according to the type of plants (climbing or non-climbing) and the place of plantation [21, 22]. Green façades use climbing plants to climb on the façade surface or a structure connected to the façade and their growing medium is almost at the foot of the façade on ground or in the pots at different heights of the building [21, 22]. Green façades have three types: traditional green facades, double-skin green façades and green curtain and perimeter flower pots [21]. In traditional green façades the plants stick to the façade while in double-skin ones a supporting structure

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will support them [Fig. 2.a]. Double-skin façades have different systems like modular trellises, wired, and mesh structures [21-23] [Fig. 2.b]. Living walls are made of panels and/or geo-textile felts, which are fixed to a vertical support or on the wall structure [Fig. 2.c, 2.d]. Living walls support growth medium in felts or panel modules and boxes as a parts of the wall structure and the building [21]. Living walls sometimes contain pre-cultivated panels or felts to be developed [22].

Green envelopes include green walls and green roofs and other exterior surfaces of the building which can be covered by vegetation [24]. Greening these surfaces by vegetation have different thermal and energy performances. These various functions can be categorized and compared according to a given criteria. The thermal properties and energy efficiency of green surfaces in buildings depend on many factors, which can be categorized as: contextual factors, greenery factors, scale factors, surface factors, and integration factors. Contextual factors refer to climatic conditions, economic factors, technical aspects, structural factors. Greenery factors include the vegetation's physical and biophysical properties. Scale factor refers to the scale of the built environment, which can be influenced by the greenery itself and the scale of the time used for assessing the thermal and energy performance of green envelopes. Surface factor are the characteristics of a building envelope's surface such as its orientation and position. Finally, integration factor is related to the way that vegetation is integrated into the building envelope's surface.

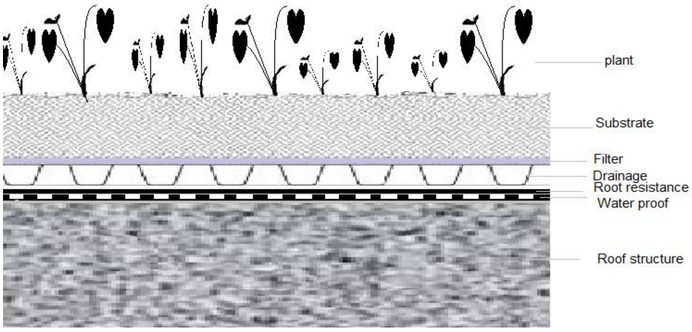

Fig. 1 The common layers of a green roof.

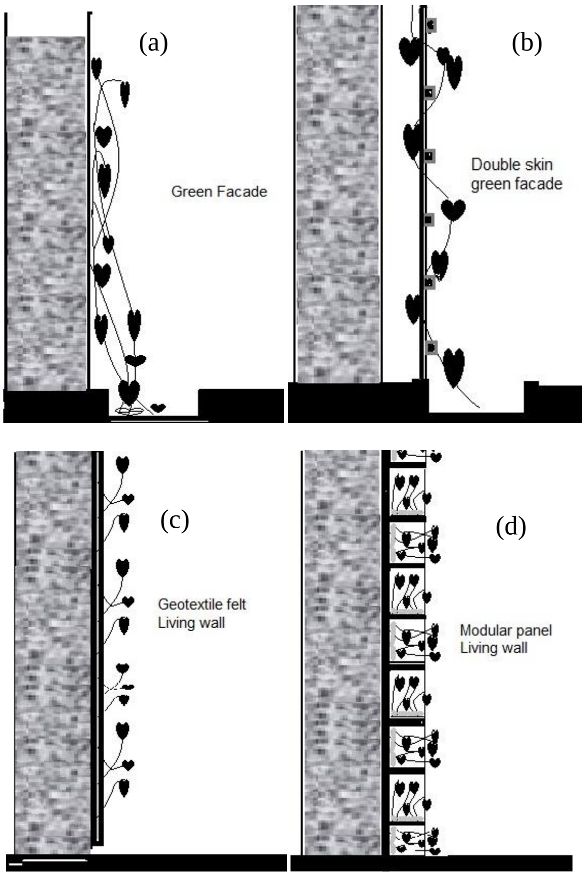

Fig. 2 (a) Green façade, the growth medium for plant is on the ground. (b) Double skin green façade, an additional structure standing beside the wall supports the greenery. (c) Modular panel living wall, the growth medium is in every box panel. (d) Geotextile living wall, the growth medium is in the felt layers or packets sticking or hanging from the wall

2. Contextual Factors

There is much research about the energy saving benefits of green envelopes and their role for passive cooling. Although these researches studying the thermal and energy performance of green envelopes belong to different geographical locations, only a few refer to the climatic conditions and their role in the parameters of the study. Here the context of different studies that considered the climatic factors is categorized according to Köppen climate classification [5, 6, 8, 17, 18, 25-42].

2.1. Green roof contextual factors

There were several studies considering the thermal properties and energy efficiency of green roofs in different climatic conditions [Fig. 3]. S.W. Tsang et al studied a green roof in the tropical climate of Hong Kong and evaluated its thermal and energy performance in a theoretical model and found some dependencies between the green roof's thermal properties and environmental factors. The research demonstrates that latent heat dissipation is more efficient in tropical climate than in temperate climates, especially in sunny summer days, where it is twice other days. Comparing a green roof with a bare roof demonstrates the absorption of solar radiation depends more on shortwave radiation than long wave radition, and the heat storage and sensible heat of a bare roof is more than that of a green roof. But increasing soil water would increase its heat storage. A green roof's albedo is twice that of a bare roof. Increasing in convection coefficient causes greater latent heat dissipation for both roof types [43].

Another investigations about extensive green roof was conducted in Athens, Greece, in the Mediterranean climate. This study shows that a green roof can reduce cooling energy in the summer by about 40%, but the reduction of heating energy in the winter is small [10, 44]. In Midwestern U.S. climate with hot-humid summers and cold-snowy winters, an extensive green roof has lower heat flux than a bare roof in all seasons, especially in summers. This indicates the energy saving properties of green roofs with more effectiveness in summer. Also a bare roof has more temperature fluctuations than a green roof during the year [45]. In the cold weather of Ottawa, Canada, extensive green roof empirical experiments demonstrate the reduction and modification of roof temperature fluctuations with moderating heat fluxes mostly in warmer months. Daily Energy consumption reduces about 75% in summer days [46].

Comparing the impact of latitude on the efficiency and energy performance of extensive green roof was explored in Mediterranean area with three different latitudes. Barcelona was selected in the north with Cairo in the south and Palermo in the middle, all in mild climates but with differences in rainfall, air temperature and humidity, which depend on solar radiation and geographical latitude. These are important factors to determine the energy needs of buildings, considering the climatic conditions. The northern region depends more on heating, while the middle region needs both heating and cooling, and the southern region has more cooling needs. The results show the importance of soil water content for more effective cooling. But good heating performance was achieved with dry soil, which means lower energy to heat. So soil moisture acts differently depending on thermal needs [47].

The cooling effect of extensive green roof proved to be adequate for the warm summers of Yamuna Nagar in India with a humid-subtropical climate [48]. Extensive green roofs can contribute to energy efficiency in buildings within the temperate climate of Florianopolis, Brazil through reducing heat gain in warm seasons about 92% and increasing heat loss about 49% in comparison with ceramic roofs. In the cold season, green roofs reduce heat gain by 70% and reduce heat loss by about 44% in comparison with ceramic roofs [49]. Another study shows improvement in thermal comfort and energy performance using extensive green roofs in La Rochelle, France [50]. The climate has a significant effect on transpiration rate and so the latent heat loss and energy transmission of the roof.

The highest rate of performance is in autumn for the tropical climate of Hong Kong. Wind has no significant effect on heat loss in different seasons. Heat dissipation is not enough as the result of high humidity and dense plant leaves in the summer. Climatic factors have an important role to determine the temperature at different heights of the canopy and the soil surface. These factors are not significant in determining the temperature and humidity in different depths of the soil. In winter, intensive green roof dissipates great heat flux to the ambient air, which necessitates more energy to warm the indoor spaces. The intensive green roof has an opposite performance in the cold seasons of temperate climates, because it functions as thermal insulation and reduces the heat flux to ambient air. In this case, lower amounts of energy are needed for heating in cold seasons of such climates. When raining, because of soil water absorption, the heat capacity of the soil increases and it saves more energy relating to heat storage and soil insulation performance [16]. Intensive green roofs in the humid subtropical climate of Hong Kong show very good thermal performance. Even 10 cm soil thickness is enough to prevent heat penetration into the interior spaces. Seasonal weather conditions have important impact on cooling performance of the roof [51]. An intensive green roof with 100 cm soil thickness in Hong Kong was explored for its components thermal function. The tree canopy would decrease the direct radiation on the roof by creating shading, while at the same time, it prevents air movement on the roof surface and increases air temperature. The substrate reduces the thermal fluctuations of the roof. Also the roof has good thermal insulation properties in the warm season and seasonal weather conditions affect transpiration of the plants on the roof and control the cooling impact of the roof [51].

Fig. 3 Green roof studies that consider climatic factors in different climates such as arid, tropical wet, mediterranean, humid subtropical, marine west coast, humid continental

From the economical and structural point of view, extensive green roofs have the advantage of having lower weights and costs for construction and maintenance in comparison to intensive green roofs. So the extensive green roof has the potential to be installed on existing building roofs and roof retrofittings, and it can help creating thermal insulation and better energy performance in older buildings in the UK climatic conditions [7]. Vegetation development over time (three year) on extensive green roofs in Sweden demonstrates an increase in moss growing in the substrate. Sedum album and sedum acre were the most surviving species. There is a need for the development of other green roof techniques, because existing techniques have a low potential for creating biodiversity in plant types [26].

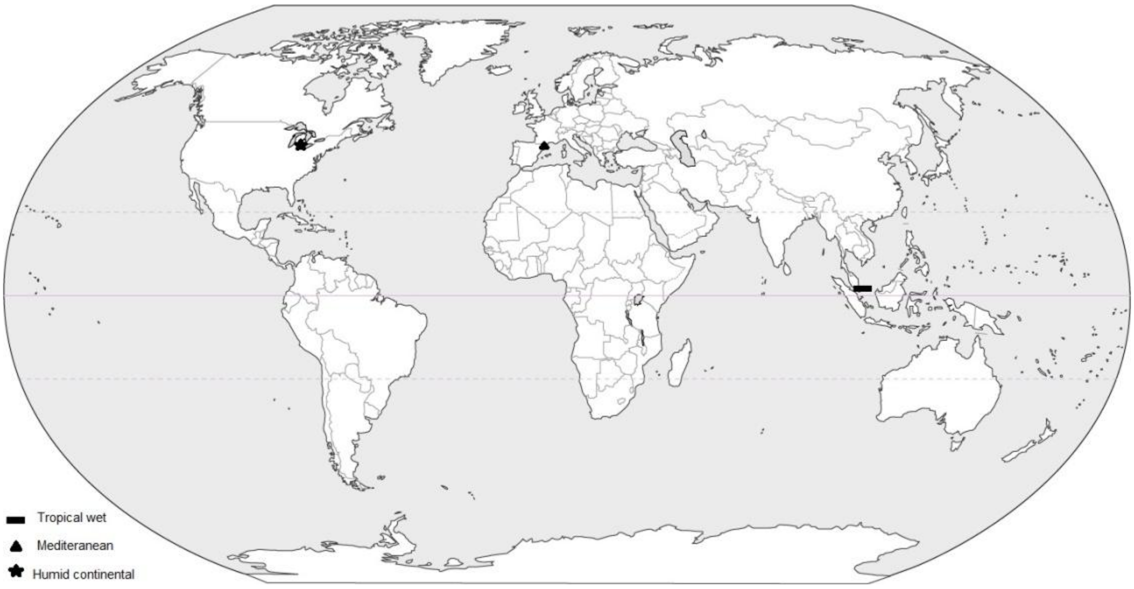

Fig. 4 Green wall studies done so far considering climatic factors in different climates such as Tropical wet, Mediterranean, Humid continental

2.2. Green walls' contextual factors

Plants on the façade have different advantages considering the climatic conditions and seasons [Fig. 4]. In warm climates and seasons, they produce a cooling effect as a result of shading and cutting solar radiation, while in cold climates and seasons, evergreen plants function as thermal insulation. So generally, greenery on the facade can help create a more efficient thermal performance and so more energy saving [45]. Investigating energy saving properties of green façades in the dry Mediterranean Continental climate of Spain came to the conclusion that because of greenery shading, a microclimate in the cavity between greenery and the wall is created, which has a lower temperature and higher relative humidity in comparison to ambient air. Moreover, the greenery also works as a wind barrier. But, there was no conclusion about the green wall insulation properties [39]. Another research in Spain addresses the energy saving and storage of green roof and double skin green façades in autumn and winter. This research came to the conclusion that in such a climate, a slight increment in the temperature was observed in the distance between the greenery and the wall (in comparison with ambient air) and there was a low reduction of wall surface temperature [23]. In the tropical climate of Singapore, the effect of different green walls on thermal comfort and energy consumption was studied and their thermal insulation performance was proved [52].

From an economic point of view, a direct green façade is the cheapest green wall system, because of its low maintenance and the materials needed to support it. On the other hand, living walls and indirect green facades are expensive types because of the design complexity, supporting structure and more maintenance and materials needed to maintain the greenery [53]. All the studies demonstrate the green wall thermal effectiveness in cold and warm seasons, which lead to more energy efficiency.

3. Greenery Factors

Greenery factors include the vegetation's physical and biophysical properties. Physical properties of plants refer to their height, foliage density and geometry with dimension characteristics [Table 1], while biophysical properties are related to transpiration, photosynthesis and evapotranspiration characteristics of the plants [Table 2] [16].

Table 1 Greenery physical properties for green roofs and green walls which are mainly mentioned in the literature

Green roofs	Plant height	color	$LAI = \frac{\text{Leaves Area}}{\text{Substrate Area}}$	Foliage density	Plant species
Green walls	Leaf shape	Foliage density	Shading coefficient	Greenery coverage ratio	

Table 2 Greenery biophysical properties for green roofs and walls (envelopes)

Green envelopes	Photosynthesis	Absorption	Evapotranspiration	Convection	Reflection

Plants create shading and so they cut direct solar radiation on surfaces and therefore prevent heating from radiation. Also, their leaves have transpiration and photosynthesis which absorbs solar radiation and convert sensible heat to latent heat. So they can reduce ambient air temperature.

3.1. Green roof greenery factors

Plants suitable for extensive green roofs in the Humid Subtropical Climates of Taiwan have better cooling effects considering their height, color and type. This resulted in an optimum height of 35 cm followed by heights of 15 cm and 10 cm respectively. Also plants with green leaves other than red and purple have better cooling effects. It is better if plants are chosen for their drought resistance [31]. Heat flux of extensive roof is sufficient to keep indoor temperature at 25º C in average in New Delhi, India. The cooling function of the roof is related to the Leaf Area Index of greenery to be 4.5. LAI is an important factor for creating a microclimate distinguished from ambient under vegetation canopy. The increasing LAI leads to a reduction of air temperature and its fluctuations under canopy and decreasing of heat flux penetration to indoor spaces, while it also increases the thermal insulation of the roof [48]. Foliage density is proved to be an effective physical parameter for extensive green roof thermal performance and energy balance. In a summer day there was a 30°C difference between the green roof and the concrete slab outer surface temperature and generally the temperature changes was correlated with foliage density directly [50].

Biophysical properties of extensive green roof affect its thermal energy balance with water saturated soil. Evapotranspiration have the most impact on heat dissipation and then it is long wave radiation emissions to cool the roof. Photosynthesis absorbs heat and prevents it from penetrating into indoor spaces. Soil and plants heat storage is less than 1% of the whole thermal energy gain. Almost all of the roof heat gain is related to solar radiation and convection is negligible. Considering green roof different layers and the role of each one in thermal function of the roof, sedum heat gain is 99.1% from solar radiation with only 0.9% from convection. Biophysical functions of the greenery contribute to roof heat dissipation, which accounts for evapotranspiration, long wave reflection and photosynthesis being 58%, 30.9% and 9.5% respectively. Only 1.2% of total heat gained would be stored in green roof and transmitted to indoor spaces [54]. Planting drought enduring plants with large coverage ratio and burned sludge substrate lead to better thermal function of green roof in the south Taiwan climate [55, 56].

3.2. Green wall greenery factors

Simulation of green wall thermal function on different façades shows that greenery coverage is completely effective in decreasing the mean radiant temperature of glass facades. Also for having more cooling effects and more thermal insulation, the shading coefficient of plants[1] needs to be low and this has linear correlation with leaf area index in a negative way. Greenery coverage is a more influential factor than shading coefficient. Optimum results are obtained with high leaf area index and low shading coefficient, which are the result of more density and covering ratio of foliage [52].

Ivy covered green walls with a supporting grid was mathematically modeled to investigate its thermal function affected by physical and geometrical properties of the green wall. The main greenery physical variations were considered as: covering ratio[1], green density[2] and leaf shapes[3]. The main factors controlling green wall thermal function are greenery density, covering ratio and geometrical properties of supporting grid. Heat flux transition to building increases as a result of larger distance of grid cables to a critical point and decreasing in foliage covering ratio. Covering ratio is the most important factor influencing heat flux. If its value is less than 30%, its thermal function is much like a bare wall. But if coverage ratio is 100%, it can cut solar gain up to 40%. Shaded area of the wall is not only determined by coverage ratio but also by foliage density. Foliage density equals coverage ratio when it is 1 and it can affect reducing heat flux to indoor up to this rate. Larger amounts of foliage density slightly decreases the heat flux to indoor spaces [57-63] .

There was no study considering the biophysical properties of plants influencing the thermal function of green vertical systems.

4. Scale Factors Impact

Greenery has many advantages as it conditions the climatic factors in different scales. Scale factor takes into consideration the scale of the greenery impacts from energy and thermal point of view which can be categorized into three scales: macro-scale for urban areas, meso-scale for buildings and micro-scale for building parts or elements.

4.1. Green roof impact scale factors

Green roofs' benefits have been explored in the two scale of building and urban area in New York City. Vegetation density decreases the air temperature of an urban area, while in the building scale, it increases the roof albedo and thermal resistance of roofs because of the plants' biophysical processes. Monitoring four locations in New York City to investigate the influence of the green area on air temperature shows a 2degrees C difference between the largest and smallest green areas' temperature. The surface albedo is an important factor to determine roofs' thermal behavior. White and green roofs have greater albedos than a black roof. Extensive green roof thermal insulation is mainly affected by its albedo and its vegetation biological activities. Also green roofs can decrease the maximum energy consumption of buildings. Changing black roofs to green roofs would affect the thermal function of roofs in a positive way and so reduce energy consumption in different scales of building and urban areas [30]. Green roofs can increase green areas in cities. Green sites would decrease air temperature, which can be on average about 0.9°C cooler than bare sites in UK parks. The greater green area and more tree numbers would result in more cooling effects in days. This is despite the fact that there is a need for future studies on greenery types and its distribution on cooling effect [64].

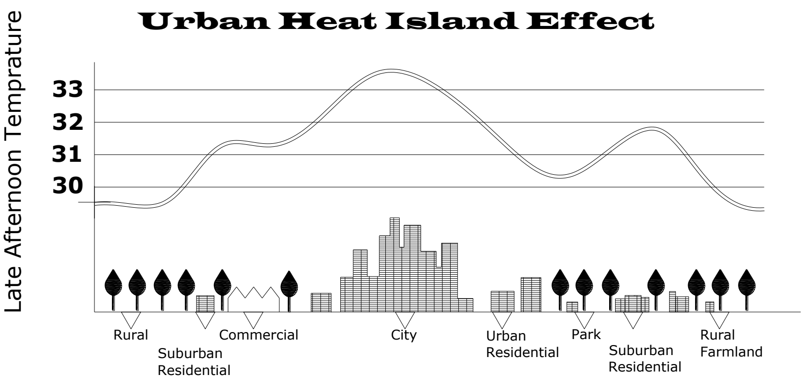

Fig. 5 Urban Heat Island effect, shows increase in temperature over cities. Green roofs can help decrease in temperature in large scale for urban areas

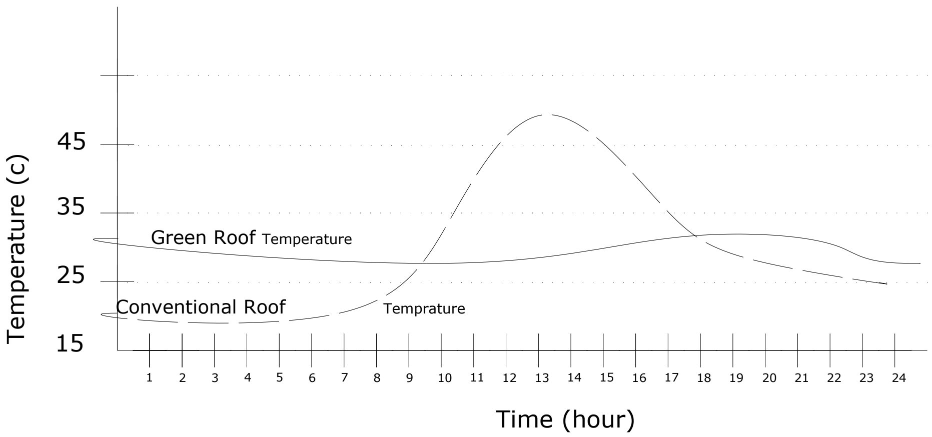

Fig. 6 Comparing green roof temperatures with conventional roof temperatures during a 24 hours period shows much less fluctuations in temperature with less need for cooling. It is the small-scale impact of green roof on energy consumption

Considering that plants' CO_2 consumption during the day is more than night, they can reduce CO_2 concentrations in ambient air. An extensive green roof with low height plants and an area of 16 m^2 in a sunny day in the tropical climate of Hong Kong shows a 2% reduction in CO_2 levels. Reducing CO_2 concentration in the environment depends on plants conditions, air flow, and the position of the green roof [17].

3.4. Green walls impact scale factor

Mechanism of passive cooling in green walls is related to the shadow creation by leaves, solar heat absorption and dissipation by greenery which act as thermal insulation and cooling through evaporation and vegetation transpiration. Green walls reduce wind velocity by acting as wind barriers. Exploring a double skin green wall demonstrates the creation of a microclimate between greenery and wall with lower temperature and higher relative humidity than the ambient air in dry continental climatic condition of Mediterranean region [21].

Sensible reduction of minimum air temperature through large regions occurs while increasing greenery covering ratio of facades. Green walls can reduce urban heat island effect with greenery coverage ratio as the most influencing factor [52].

5. Building Envelope Surface Factors

The materials and layers of building envelope surfaces can make a big difference in the thermal behavior and energy efficiency of the surface, which accomodates the greenery. Building envelope includes different surfaces with different positions and directions which cause differentiation in their thermal properties and therefore energy performance. Roofs as horizontal surfaces, receives more radiation in summers, while walls are vertical surfaces which receive direct radiation according to their geographic direction [65].

5.1. Green roof surface factors

For the most part, green roof thermal properties were explored considering greenery thermal function. Studying thermal properties of abiotic parts of green roof in Hong Kong shows different results with regards to decreasing thermal insulation of densely vegetated green roofs in comparison with bare roofs in temperate climates. A water storage layer, with its water content has the evaporative cooling role that increases the specific heat capacity of the roof. The drainage layer with its porous structure contains stagnant air, which increases the roof's thermal resistance and insulation [9] [Table 3]. Comparing different roof types in Kobe Japan, demonstrates that extensive green roofs have low heat flux like high-reflecting white roofs because of the greenery evapotranspiration, which cause large latent heat flux. But the gray high reflective roof and concrete roofs have large sensitive heat flux [20, 45, 66-68].

The influence of mass transfer of green roofs, aside from its heat transfer, was ignored in most studies, though latent heat in condensation and evaporation processes conveys energy. Findings show that heat and mass transfer have different processes in green roofs in comparison with bare classical roofs. Green roofs improve the thermal behavior and energy saving of the building. As using hygroscopic materials in the building reduces the energy consumption, the importance of moisture factor in green roofs becomes obvious [50].

Table 3 Thermal function of green roof layers [9].

Roof layer	Water storage	Drainage
Thermal function	Increasing evaporative cooling Increasing specific heat capacity	Increasing thermal resistance Decreasing heat transfer

5.2. Green wall surface factor

The influence of wall direction on green wall energy efficiency was investigated and the results show a small difference in air temperature between wall and greenery in south directions which has the least value for south east and the most for south west direction. The east direction facades as (N.E, E, and S.E) have the lowest temperature. The south west façade had the highest relative humidity among others [23].

6. Integration Factors

Integration factors refer to the way greenery is integrated into the building envelope. This is mainly related to the green roof or green wall type or the arrangement of different parts and layers in the building envelope [61, 69].

6.1. Green roof Integration factors

Inverted roofs would decrease the merits of a green roof. Inverted extensive green roofs have smaller thermal fluctuations and lower peak temperatures in comparison with inverted gravel ballasted roof in Michigan, USA. Extensive green roofs reduce heat transition through roofs by about 167% in summer as the highest rate and 13% in winter as lowest rate in comparison with gravel roofs. The most important factors, which affect the different performance of the roofs, are air temperature, solar radiation and the amount of moisture in the growing medium. Snow is a controlling factor in winter. Extensive green roof reduces energy consumption during a year. The decrement of energy consumption is determined by climatic condition, roof type, plant types, growing media depth and composition, and the amount of irrigation. Increasing the growing medium's depth increases the leaves area and biomass with more biophysical effects and impact. In tropical climatic conditions, the results may be not the same and plant type selection would be different [45]. The roof garden in Hong Kong has different ecological and energy performance in comparison with an extensive type. It has lower transpiration rate and thus lower latent heat loss. Intensive green roofs create a distinguished microclimate under their canopy. The canopy slows down the wind and stores heat released by the roof so its heat loss is decreased and its thermal resistance is reduced relatively. But its heat loss is buffered in rainy weather. The canopy cut 80% of solar radiation reaching the soil and roof and its albedo differs according to wavelength from 40% for near infrared radiation to 6% for photosynthetic active radiation. Tropical intensive green roofs have less thermal insulation and cooling efficiencies in comparison with temperate climate regions [14].

6.2. Green wall integration factors

The thermal performance of different green wall types was examined in Singapore. Living wall types as Modular panel, Grid and modular ones have the best cooling effects for maximum wall surface temperature. Reducing the diurnal temperature fluctuations of wall surfaces and ambient air is achieved more effectively by living wall with modular panel. This is while Green façade type as Modular trellis had no considerable impact on reducing ambient air temperature [70]. The impact of different types of green wall systems on ambient air velocity and temperature as well as wall surface temperature was explored and compared with bare wall in three different cities of Netherland. All green walls have lower surface temperatures in comparison with bare wall thanks to their leaves shading. Also wind velocity reduction was observed inside foliage and the cavity behind, which increases the thermal insulation of the wall in direct green façades. Living wall with planter boxes is the most effective wind barrier than other types because of its air cavity. Also it shows more thermal insulation efficiency in cold weather. But the cavity thickness has an optimum size between 4 to 6 cm to decrease wind velocity. All these studies demonstrate the green walls' thermal effectiveness in cold and warm seasons which lead to more energy efficiency [53].

7. Discussion

Exploring energy performance of building envelope surfaces depends on their thermal function. As the sun path changes during a day and a year, the sun position and geographical latitude determine the amount of solar radiation reaching the earth. On the other hand, the greenery and surface properties affect the green envelope's thermal behavior and so it's energy performance.

Reviewing existing literature shows that there is a gap in comparing energetic performance of green roofs with green walls. This is may be due to their different structural system and position. But, considering the fact that horizontal surfaces receive more solar radiation with greater intensity in summers than vertical surfaces, it is safe to assume that their heat gains are more. It can be concluded that green roofs can have more cooling effects than green walls because reducing their heat gain by greenery will help create more cooling. But there are other factors to be considered, such as the ratio of roof area to the building volume, or the size of roof area in comparison with the area of the walls. Another gap in data is the lack of adequate studies about certain types of green envelopes over the others. For instance studies about intensive green roofs are very few in comparison with extensive green roofs. This may be the result of a more widespread construction of extensive roofs and the greater complexity of modeling and evaluating intensive roofs. Another factor is the low diversity of climatic types in which green envelope performances were studied. We can discuss the green envelopes energy efficiency according to the factors they were classified.

7.1. Contextual factors

Firstly, we can compare the function of green roofs in different climates. As solar radiation intensity, relative humidity and air temperature are the main climatic factors, which differ in different climates and affect the thermal performance of envelopes, the comparison between green roofs in different climatic condition can be useful. According to the literature in tropical climates, the latent heat dissipation plays an important role in the cooling effect of green roofs, so airflow velocity, which helps this phenomenon, helps cooling. It seems extensive roofs have more efficiency than intensive ones in tropical climates because the intensive types calm airflow on the roof surface.

In temperate climates the latent heat dissipation is not as important as tropical ones. It is because of the lower relative humidity, which allows more evaporation cooling. In winter the intensive green roof loses more thermal energy in a tropic climate in comparison with a temperate climate because of less soil moisture. As the intensive roof absorbs and stores some of the reflected heat from the roof in the air under its canopy, it is more efficient than an extensive type for cold seasons.

Shortwave radiation is the main key factor for solar radiation absorption in tropical climate, so shading would be very effective to lower the surface and air temperature. The greenery albedo is high in tropical regions because of the more clean and clear surface of leaves as a result of more raining and more direct solar radiation. Green roof reduces temperature fluctuations and heat flux in cold climates and it works as thermal insulation. Moreover, it has the most efficiency in the summer. In temperate climates, green roof performance is good in both warm and cold seasons with more efficiency in warm seasons. Green roofs increase thermal insulation, so both heat gain and heat loss are decreased. In some regions, heat gain reduction is up to 90%. Green roofs function efficiently in four seasons of the humid continental climate with cold snowy winters and hot and humid summers, with most efficiency for cooling in the summers. In the

Mediterranean climate, the cooling effect is good while decrease in heat loss is not significant for winters.

Soil moisture has direct relation with roof cooling but it has diverse effects for the roof's thermal performance in the winter. In monsoon climatic conditions, green roofs are very effective for cooling. There was no considerable research in arid climates for green envelopes in comparison with other climatic types. In fact, most of the studies about green roofs' thermal performance were conducted in temperate and tropical climates other than harsh climates. This is despite the fact that the benefits of greenery in harsher climates is much more necessary in comparison with moderate climates.

For green walls in tropical climates, the thermal insulation of the wall is increased by greenery. But in dry continental climates, though the cooling effect was good, the thermal performance of the green wall in winter is not considerable. Though using indirect green walls would decrease airflow rate behind the greenery, which would decrease heat loss in winter by evergreen plants.

7.2. Greenery factors

In tropical climatic conditions, the greenery factors which mainly affect the thermal performance of green roofs are covering ratio, plants height and color. The main biophysical processes for green roofs in the Tropics are evapo-transpiration and albedo. While in the temperate climate, the foliage density is the most important factor for green roof thermal performance, in continental monsoon climate, the leaf index area of green roof is the most effective parameter in determining the roof's thermal behavior. In the tropical region, the main factors of green walls that help cooling are coverage ratio and foliage density. In supported green façades, the dimensions of support structure grids affect the foliage density. Greenery reflects much more near infrared radiation than visible (PAR) radiation.

7.3. Impact Scale Factors

Green roofs [Table 4] and green walls [Table 5] have considerable impacts on different scales of the built environment. In macro scale, increasing green areas in the urban area decreases the air temperature and CO_2 levels, which mitigate the urban heat island effect. For building as meso-scale, the greenery improves thermal properties of the building envelope, which results in energy savings in buildings. Moreover, plants help with the creation of a microclimate with more moderate condition than the ambient. Greenery determines the material properties of abiotic parts of building envelope, which support it, and affects their thermal and energetic functions in micro-scale.

7.4. Surface factors

Extensive green roofs have higher albedo than bare and concrete roofs and its reflection is near those of white roofs. Densely vegetated roofs in tropical climate conditions show lower thermal insulation in comparison with temperate climate. The green roof moisture exchange with the environment cause it to be more energy efficient than a bare roof.

Green wall directions influence its temperature, which corresponds to sun path geometry and its variations according to time. So the most cooling effect is seen in west directions while the least is for east directions. The south directions have higher air temperature behind the greenery, which is small in winter. But there is a need for more researches exploring these aspects.

Table 4 Green roofs impacts on the built environment in different scales that are derived from literature

	Micro-scale impacts	Meso-scale	Macro-scale
Green roofs	Reducing ambient air co2	Increasing roof albedo	Decreasing air temperature
	Decreasing air temperature	Increasing roof thermal resistance	Increasing green areas

Table 5 Green walls impact on the built environment in different scales, which are derived from literature

Micro-scale impacts	Meso-scale	Macro-scale
Increasing relative humidity	Increasing passive cooling	Decreasing air temperature
Decreasing air temperature	Increasing wall thermal resistance	Increasing green areas

7.5. Integration factors

Intensive green roofs have different thermal behaviors in comparison with extensive roofs. One reason is related to the fact that intensive green roofs have more thickness and mass which causes more thermal inertia than extensive roofs and so it would store more heat. The other is related to its larger plants and higher canopy. The intensive green roof traps air under its canopy and so slows down the airflow. So it decreases the heat exchange through convection and has less efficiency in humid climates. But in other climatic types the thermal benefits of intensive green roof is more than the extensive ones because of more biomass and so more biophysical functions. Green roofs improve thermal behavior of roofs in general but the position of the insulation layer in the roof can affect its thermal efficiency. Inverted roof would cause a reduction of thermal efficiency of the green roof. It is because of the insulation is above the roofing membrane.

Living walls, especially modular panel or planted box ones, show more cooling effect than other green wall types. It is because of the cavity between their foliage and the façade. Living walls create more shade so cause more cooling effect. Also they can trap air much more than other types inside the cavity and so reduce wind flow and create a more distinguished microclimate inside the cavity than other green walls, which cause more thermal insulation. Besides, they have more mass which increases their thermal inertia.

Table 6. Main factors and their related variables according to discussion

Factors	Type	Variable	Variable	Variable	Variable	Variable
Contextual factor	Green roof	Latent heat dissipation	Calming air flow	Soil moisture	Shading	Thermal resistance
	Green wall	Thermal resistance	Calming Air flow			
	Impact Scale	Micro scale	Meso scale	Macro scale		
Impact scale factor	Green roof	Ambient air co2	Roof albedo	Air temperature		
		Air temperature	Thermal resistance	Bio physical		
	Green wall	Relative humidity	Passive cooling	Air temperature		
		Air temperature	Thermal resistance	Bio physical		
Surface factor	Green roof	Roof layers materials	Plant albedo	Moisture exchange	Vegetation dense	
	Green wall	Geographic directions	Green density			
Integration factor	Green roof	Thickness and mass	Canopy height	Bio physical function	Position of roof insulation	
	Green wall	Air cavity	Thickness and mass	Shading	Structure Geometry	
Greenery factor	Green roof	Plant color	Plants height	The leaf index area	Covering ratio	Plant albedo
	Green wall	Green density	Covering ratio	Structure Geometry		

8. Conclusion

According to literature review we can categorize the main factors affecting the thermal performance and energy consumption of the buildings with green envelopes within five main categories.

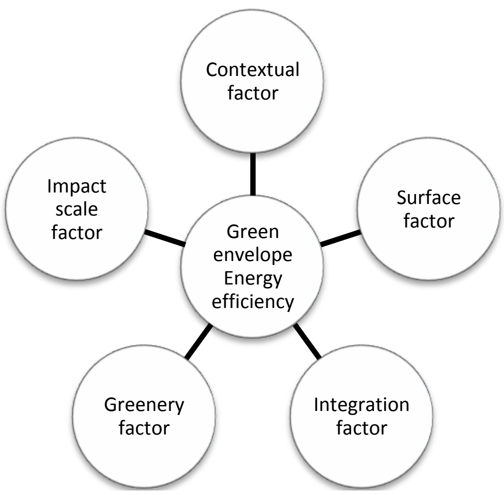

Fig. 7 Classification of factors affecting green envelops energy efficiency

By way of a general conclusion, it can be deduced that greenery improves the thermal performance of building envelopes and thus results in more energy efficiency and energy savings.

- Main greenery physical properties, which affect the green envelope thermal and energetic functions, are density, height, LAI, covering ratio and color.
- The physical, structural and geometrical properties of surfaces, which support greenery, affect the thermal behavior of green envelope.
- Generally, green envelopes improve the thermal function and energy performance of buildings in all climatic conditions with most efficiency for cooling in summers.
- Arranging roof layers would influence the thermal performance of green roofs. Properties of roof layer materials determines the thermal behavior of green roofs. But, improving their function depends on climatic conditions, which determines the types of plants and type of integration of greenery into the envelope.
- The built environment benefits from green envelopes in different scales.
- The direction and position of the green surface in building envelope would determine its energetic role.
- This study demonstrates the gaps in studying the thermal performance of green walls in comparison with green roofs in different climates.

Note

1. shading coefficient of plants = solar radiation beneath plants to the solar radiation hits the plants.
2. Covering ratio= percentage of the wall area covered by greenery.
3. Green density = surface area of leaves within covering area.
4. Leaf shapes = categorized to simple leaf, dissected leaf, and compound leaf.

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