GREEN ENVELOPES CLASSIFICATION: The comparative analysis of efficient factors on thermal and energy performance of green envelopes

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ABSTRACT

This paper classifies the green envelopes to compare their thermal and energetic functions in more effective way. In this case we consider any type of green roof and green wall under definition of green surface of building envelopes, which is called together green envelopes. After a literature review of applying different types of green surfaces in building envelopes in different climatic conditions, considering different factors we came to a classification of green surfaces in building envelopes. This classification is done according to some effective factors which were derived from literature to compare the green envelopes. The classification is based on several factors including contextual factors, greenery factors, scale factors and surface and integration factors. Contextual factors refers to the environmental and natural conditions in which the surface exists, greenery factors includes the vegetables physical and structural characteristics, scale factors stands for the scale, which green surface has influence on the environment , surface factors is about the properties of the building envelope surface which greenery is attached to such as orientation, position, type of materials and finally integration factors refers to the way greenery is attached to building envelope. Finally the study demonstrates the influence of physical and geometrical properties of plants and their supporting structures to affect the thermal performance of green envelopes. Climatic condition has an important role on thermal behavior of green envelopes and it determines the types of plants and greenery integration into envelope. Also green envelopes would benefit the built and natural environment in different scale.

Key words: green roof, green wall, thermal function, energy performance, living envelope

INTRODUCTION

Green envelopes in this paper are greening on any surface of the building envelope. Mainly these green surfaces are known as green roofs and green walls. Using greenery on building exterior surfaces dates back to very long ago. From one point of view, it was foliage and tree branches which made the first houses for human [1]. The hanging gardens of Babylon which dates back to 2000 to 3000 years before was one of the most famous examples of using greenery on building surfaces [2]. The other example is the traditional Scandinavian sod roofs with low slope, which were widespread through many rural areas of Scandinavia for its thermal insulation function [3]. Also dating back to 3rd century BC till 17th century AD, Romans used trellises for growing grape on villa walls [4].

Modern greenery systems on roofs include two main types as extensive and intensive [5-7]. Intensive and extensive green roofs have the same layers as: From top to bottom, a typical green roof consists of several layers: (1) vegetation, (2) substrate, (3) filter membrane, (4) drainage layer, and (5) root resistance layer. Plants cultivated on green roofs ranging from native plants and grasses to drought tolerant types such as Sedum and Delosperma species, which belong to the cactus family of plants [8] [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 ground level. They generally require substrate depths greater than 20 cm to 120 cm and generally require ‘intense’ maintenance. Comparing extensive green roofs to intensive ones, they are lighter and cheaper with lower capital cost and needs 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, herb or drought-tolerant sedum [5].

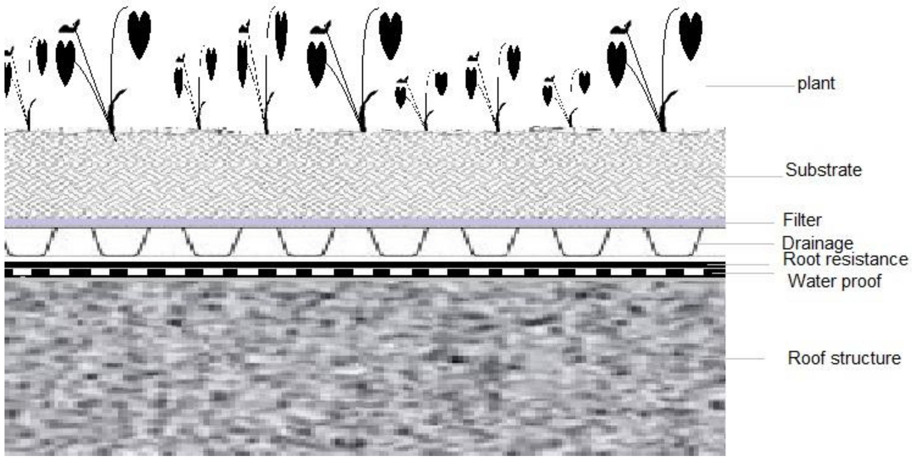

Figure 1. Green roof general layers

Green walls or green vertical systems can be divided into two different categories according to the level of maintenance and variety of plant types which can be used in them, intensive green walls need more care and use more types of plants [9] [10]. but green walls mainly classify in two main categories as green façades and living walls according to the type of plants (climbing-no climbing) and the place of their planting medium [9, 10]. Green façades use climbing plants to climb on façade surface or a structure connected to façade and their growing medium is almost at the foot of the façade on ground or in the pots at different height of the building [9, 10]. Green façades has three types as traditional green facades, double skin green façade or green curtain and perimeter flower pots[9]. In traditional green façade the plants stick to façade to develop while in double skin ones a supporting structure will support them [Fig. 2.a]. Double skin façades have different systems as modular trellises, wired, and mesh structures [9-11] [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 building [9]. Living walls sometimes contain pre-cultivated panels or felts to be developed [10].

Green Envelopes include green walls and green roofs and other exterior surfaces of the building which can be covered by vegetation. Greening these surfaces by vegetation have different thermal function and energetic performances. These various functions can be categorized and compared according to some criteria. Thermal and energetic properties 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 vegetation physical and biophysical properties. Scale factor refers to the scale of the built environment which can be influenced by greenery and scale of the time for considering thermal and energetic aspects of the green envelopes. Surface factor are the characteristics of a building envelope surface as its orientation and position. And finally integration factor is related to the way that vegetation is integrated into the building envelope surface.

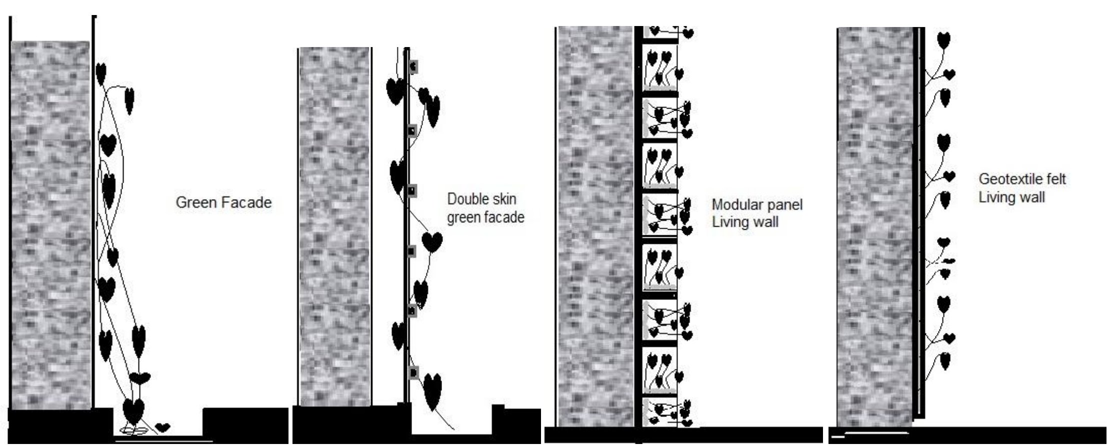

Figure 2. a) Green façade, the growth medium for plant is on the ground. b) Double skin green façade, an additional structure standing beside the wall supports the greenery. c) Modular panel living wall, the growth medium is in every box panel. d) Geotextile living wall, the growth medium is in the felt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

1. CONTEXTUAL FACTORS

There exist quite large number of researches addressing the energy saving benefits of green envelopes and their role for passive cooling. Although papers studying the thermal and energy performance of green roofs belong to different geographical locations, few ones referred to the climatic type of the region and its role in the parameters of the study. Here the climatic context of different studies which considered the climatic factors is categorized according to Köppen climate classification.

1.1. 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 tropical climate of Hong Kong and evaluate its thermal and energy performance in a theoretical model and found some dependencies between green roof thermal properties with environmental factors. The research demonstrates that latent heat dissipation is more efficient in tropical climate than temperate climate especially in summer sunny days which it is twice. Comparing green roof with a bare roof demonstrates the absorption of solar radiations depends more on shortwave radiation than long wave, and the heat storage and sensible heat of bare roof is more than green roof. But increasing soil water would increase its heat storage. Green roof albedo is twice that of the bare roof. Increasing in convection coefficient causes greater latent heat dissipation for both roof types [12]. Another investigations about extensive green roof was conducted in Athens, Greece in Mediterranean climate shows that it can reduce cooling energy in summer about 40% , but reduction of heating energy in winter is small [13, 14]. In Midwestern U.S. climate with hot-humid summers and cold-snowy winters, extensive green roof has lower heat flux than bared roof in all seasons especially in summers. It indicates energy saving property of green roof with more effectiveness in summer. Also bare roof had more temperature fluctuations than green roof during a year [15]. In cold weather of Ottawa, Canada, extensive green roof empirical experiments demonstrates reduction and modification of roof temperature fluctuations with moderating heat fluxes mostly in warmer months. Daily Energy consumption reduces about 75% in summer days [16]. 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 north with Cairo in the south and Palermo in the middle, all in mild climate but differences exist in rainfall amount, air temperature and humidity which depends on solar radiation and geographical latitude. These are important factors to determine energy needs of buildings considering climatic conditions. The north region depends more on heating, while middle region needs both heating and cooling and the south region have more cooling needs. The results show the importance of soil water content for more effective cooling. But good heating performance achieved with dry soil which means lower energy to heat. So soil moisture acts differently depending on thermal needs [17]. The cooling effect of extensive green roof was proved to be adequate for warm summers of Yamuna Nagar in India with humid-subtropical climate through experimental data [18]. Extensive green roofs can contribute to energy efficiency of building in 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 cold season it reduces heat gain 70% and reduces heat loss about 44% in compare with ceramic roofs [19]. Another study shows improving in thermal comfort and energy performance using extensive green roof in La Rochelle, France temperate climate [20]. The climate has a significant effect on transpiration rate and so the latent heat loss and energy transmit ion rate of the roof. It highest rate is in autumn for 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 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 to determine 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 cold seasons of temperate climates because it functions as thermal insulation and reduces the heat flux to ambient air. In this case lower amount of energy is needed for heating in cold seasons of such climates. When raining, because of soil water absorption the heat capacity of soil increases and it saves more energy relating to heat storage and soil insulation performance [21]. Intensive green roof in the humid subtropical climate of Hong Kong shows very good thermal performance. Even 10 cm soil thickness is enough to prevent heat penetration to indoor. Seasonal weather conditions have important impact on cooling performance of the roof [22]. 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 roof by creating shading while at the same time, it prevents air movement on roof surface and increase air temperature. The substrate reduces the thermal fluctuations of roof. Also the roof has good thermal insulation property in warm season. And seasonal weather conditions affect transpiration of the plants on roof and controls cooling impact of roof [22].

From economical and structural point of view , extensive green roofs has 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 the existed building roofs and roof retrofitting and it can help creating thermal insulation and better energy performance of older buildings in the UK climatic conditions [7]. Vegetation development over time (three year) on extensive green roof in Sweden demonstrates increasing in moss growing in substrate. Sedum album and Sedum acre were most surviving species. There can be other green roof techniques to be developed because existed techniques have low potential to create biodiversity in plant types [23].

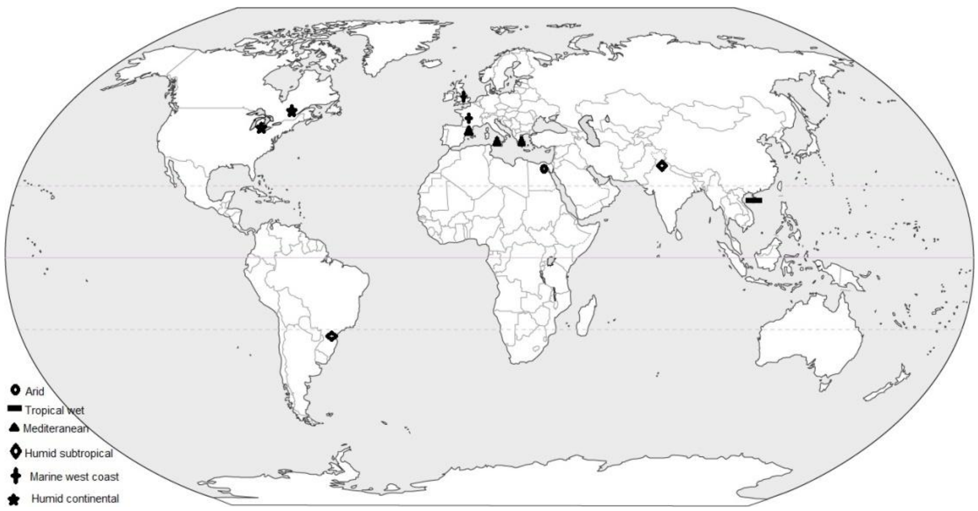

Figure 3. Green roof studies which is done so far considering climatic factors in different climates such as Arid, Tropical wet, Mediterranean, Humid subtropical, Marine west coast, Humid continental.

1.2. Green walls contextual factors

Plants on façade have different advantages considering climatic condition and seasons [Fig. 4]. In warm climates and seasons it has a cooling effect as the result of its shading and cutting sun radiation while in cold climates and seasons evergreen plants function as thermal insulation. So generally greenery on facade would help more efficient thermal performance and so more energy saving [15]. Investigating energy saving properties of green façade in dry Mediterranean Continental climate of Spain came to the result that because of the greenery shading there would be created a microclimate in the cavity between greenery and wall with lower temperature and higher relative humidity in comparison to ambient air. And the greenery works as wind barrier. But there was no conclusion about green wall insulation property [24]. Another research in Spain addresses the energy saving and storing of green roof and double skin green façade in autumn and winter. It came to the conclusion that in such climate slightly increment of temperature were observed in distance between greenery and wall in compare with ambient air while low reduction of wall surface temperature was resulted [11]. In 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 [25].

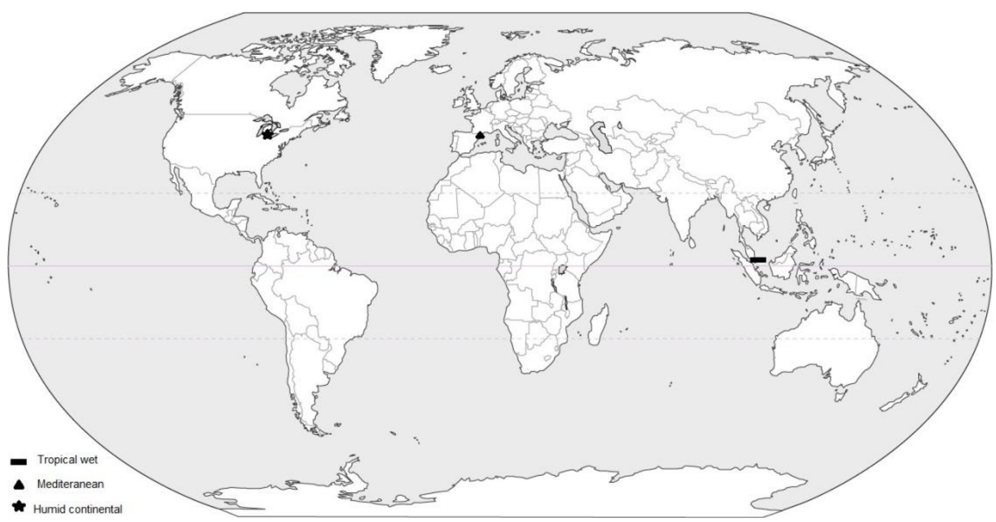

Figure 4. Green wall studies which is done so far considering climatic factors in different climates such as; Tropical wet, Mediterranean, Humid continental.

From economic point of view direct green façade is the most cheap green wall system for its less maintenance and the materials needed to support it. Whereas the living walls and indirect green facades are expensive types related to the design efforts, supporting structure and more maintenance and materials needed to survive greenery [26]. All the studies demonstrate the green wall thermal effectiveness in cold and warm seasons which lead to more energy efficiency.

2. GREENERY FACTORS

Greenery factors include vegetation 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][21].

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

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

2.1. Green roof greenery factors

Plants suitable for extensive green roof in Humid Subtropical Climates of Taiwan would have better cooling effects considering their height, color and type. It resulted in plants' height optimum of 35 cm follows with the heights of 15 cm and 10 cm afterwards. Also plants with green leaves other than red and purple have better cooling effect. Plants are better to be chosen for their drought resistance to be enough [27]. Heat flux of extensive roof is sufficient to keep indoor temperature at 25 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 in LAI lead to reduction of air temperature and its fluctuations under canopy and decreasing of heat flux penetration to indoor while it increases thermal insulation of roof [18]. Foliage density is proved to be an effective physical parameter for extensive green roof thermal performance and energy balance. In summer day there was a 30 C difference between green roof and concrete slab outer surface temperature and generally the temperature changes was correlated with foliage density directly [20].

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 roof. Photosynthesis absorbs heat and prevents penetrating it to indoor spaces in small parts. 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 account 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 [28]. 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 [29].

Green envelopes	photosynthesis	absorption	evapotranspiration	convection	reflection

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

2.2. Green wall greenery factors

Simulation of green wall thermal function on different façade shows that greenery coverage is completely effective in decreasing the mean radiant temperature of glass facade. Also for having more cooling effects and more thermal insulation, the shading coefficient of plants [i] needs to be low and this has linear correlation with leaf area index in a negative way. Greenery coverage is more influencing factor than shading coefficient. Optimum results obtained with high leaf area index and low shading coefficient which are the result of more density and covering ratio of foliage [25].

Ivy covered green wall 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 ratioii, green densityiii and leaf shapesiv. 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 as a bare wall. But if coverage ratio is 100%, it can cut solar gain up to 40%. Shaded area of 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 decrease the heat flux to indoor [30] .

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

3. 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 in three scales as; macro-scale for urban areas, meso-scale for buildings and micro-scale for building parts or elements.

3.1. Green roof impact scale factors

Green roofs’ benefits have been explored in two scale of building and urban area in New York City. Vegetation density would decrease the urban area air temperature while in building scale it increases the roof albedo and thermal resistance of roof because of the plants biophysical processes. Monitoring four locations in New York City to investigate influence of green area on air temperature shows 2C difference between largest and smallest green areas’ temperature. The surface albedo is an important factor to determine roofs thermal behavior. White and Green roof has greater albedo than black roof. Extensive green roof thermal insulation is mainly affected by its albedo and its vegetation biological activities. Also green roof can decrease the maximum energy consumption of building. Changing black roof to green roof would affect the thermal function of roofs in a positive way and so reduces energy consumption in different scales of building and urban areas [31]. 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. Though there is a need for more future studies on greenery types and its distribution on cooling effect [32] .

Considering the plant co_2 consumption in day is more than night so they can reduce co_2 concentration in the ambient air. An extensive green roof with low height plants with an area of 16 m^2 in a sunny day in the tropical climate of Hong Kong shows 2% reduction in co_2 amount. Reducing co_2 concentration in the environment depends on plants condition, the position of green roof and air flow condition [33].

3.2. 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 to act as thermal insulation and cooling through evaporation and vegetation transpiration. Green walls reduce wind velocity as wind barriers. Exploring a double skin green wall demonstrates 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 [9].

Sensible reduction of minimum air temperature through large region 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 to [25].

4. BUILDING ENVELOPE SURFACE FACTORS

The materials and layers of building envelope surfaces can make difference in the thermal behavior and energetic function of the surface which is contained the greenery.

Building envelope includes different surfaces with different positions and directions which cause differentiation in their thermal properties and so their 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.

4.1. Green roof surface factors

Mostly 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 in regard to decreasing thermal insulation of densely vegetated green roof in compare with bare roof in temperate climate. Water storage layer with its water content has the evaporative cooling role and increases the specific heat capacity of the roof. The drainage layer with its porous structure containing stagnant air increases the roof thermal resistance and insulation [34] [Table 3]. Comparing different roof types in Kobe Japan, demonstrates that extensive green roof has low heat flux like high reflected white roof because of the greenery evapotranspiration which cause large latent heat flux. But the gray high reflective roof and concrete roof have large sensitive heat flux [35-37].

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

Table 3. Thermal function of green roof layers which is mentioned in literature

The influence of mass transfer of green roof beside its heat transfer was ignored in most studies, though latent heat in condensation and evaporation processes conveys energy. Findings shows heat and mass transfer have different process in green roof in compare with bare classical roof. Green roof improves thermal behavior and energy saving of the building. As using hygroscopic materials in building reduces the energy consumption of building, the importance of moisture factor in green roof is obvious [20].

4.2. Green wall surface factor

The influence of wall directions on green wall energy efficiency was investigated and for wall directions shows low 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 [11].

5. INTEGRATION FACTORS

Integration factor refers to the way greenery is integrated into building envelope. That is mainly related to the green roof or green wall type or the arrangement of different parts and layers in the building envelope.

5.1. Green roof Integration factors

Inverted roof would decrease the merits of green roof. Inverted extensive green roof has smaller thermal fluctuations and lower peak temperatures in comparison with inverted gravel ballasted roof in Michigan, USA. Extensive green roof reduce heat transition through roof about 167% in summer as highest rate and 13% in winter as lowest rate in compare with gravel roof. The most important factors which affect the different performance of the roofs are air temperature, solar radiation and amount of moisture in 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 its composition and the amount of irrigation. Increasing growing medium depth causes increasing the leaves area and biomass with more biophysical effects and thus increasing the impacts. In tropical climate condition the results may be not the same and plant type selection would be different [15]. The roof garden in Hong Kong has different ecological energetic in compare with an extensive type. It has lower transpiration rate and thus lower latent heat loss. Intensive green roof create a distinguished microclimate under its canopy. The canopy slows down the wind and stores heat released by roof so its heat loss is decreased and its thermal resistance reduces relatively. But its heat loss buffered in rainy weather. Canopy cut 80% of solar radiation to reach the soil and roof and its albedo differs according to wavelength from 40% for near infra red radiation to 6% for photosynthetic active radiation. Tropical intensive green roof have less thermal insulation and cooling efficiencies in comparison with temperate climate regions [38].

5.2. Green wall integration factors

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. While Green façade type as Modular trellis had no considerable impact on reducing ambient air temperature [39]. 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 temperature in compared with bare wall thanks to their leaves shading. Also wind velocity reduction was observed inside foliage and the cavity behind it which increases the thermal insulation of wall in direct green façade. 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 the study demonstrates the green wall thermal effectiveness in cold and warm seasons which lead to more energy efficiency [26] .

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

Table 4. Green roofs impacts 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

Table 5. Green walls impacts on the built environment in different scales which are derive from literature

6. DISCUSSION

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

Reviewing literature shows there is a gap in comparing energetic effects and performance of green roofs with green walls. This is may be due to their different structural system and position. But according to the fact that horizontal surfaces receive more solar radiation with greater intensity in summers than vertical surfaces so their heat gain are more. It can be concluded that green roof would have more cooling effect than green walls because reducing their heat gain by greenery will help more cooling. But there are other factors to be considered as the ratio of roof area to the building volume or the size of roof area in compare with the walls area. The other gap is the lack of enough studies about some types of green envelopes other than other ones. For instance the studies about the intensive green roofs are very few in compare with extensive green roofs. This may be the result of more widespread construction of extensive roofs and more complexity of modeling and evaluation of intensive roofs. Another gap is due to the few climatic types in which green envelopes performance were studied. We can discuss the green envelopes energetic function according to the factors they were classified.

6.1. 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 climate, the latent heat dissipation plays an important role in cooling effect of green roof, so air flow velocity which helps this phenomenon helps cooling. It seems extensive roofs have more efficiency than intensive ones in tropical climate because the intensive type calm the air flow 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 losses more thermal energy in tropic climate in comparison with temperate climate because of less soil moisture. As the intensive roof absorbs and stores some of the reflected heat from roof in the air under its canopy, it is more efficient than 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 climate and it works as thermal insulation. And it has the most efficiency in summer. In temperate climates green roof performance is good in both warm and cold seasons with more efficiency in warm seasons. And green roof increase the thermal insulation, so both heat gain and heat loss decreases by green roof. In some regions the heat gain reduction is up to 90%. Green roofs functions efficiently in for seasons of the humid continental climate with cold snowy winter and hot and humid summers with most efficiency for cooling in summers. And in Mediterranean climate the cooling effect is good while decreasing in heat loss is not significant for winters. Also soil moisture has direct relation with roof cooling but it has diverse effect for the roof thermal performance in winter. In monsoon climatic condition green roof is very effective for cooling. There was no considerable research in arid climates for green envelopes in compare with other climatic types. Actually most of the studies about green roof thermal performance were conducted in temperate and tropical climates other than harsh climates. While the benefits of greenery in harsher climates is more needed to moderate the environment condition and so to lower the energy consumption.

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

6.2. 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. And main biophysical processes for green roof in Tropic are evapo-transpiration and albedo. While in temperate climate the foliage density is the most important key for green roof better thermal performance. In continental monsoon climate the leaf index area of green roof is the most effective parameter to determine roof thermal behavior.

In tropical region the main factors of green walls which 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 infra red radiation than visible (PAR) radiation.

6.3. 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 would decrease the air temperature and co_2 amount which mitigate the urban heat island effect. For building as meso-scale the greenery improve thermal properties of the building envelope which results in energy savings in buildings. And plants help to 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.

6.4. Surface Factors

Extensive green roof has higher albedo than bare and concrete roof and its reflection is near to white roof. Densely vegetated roof in tropical climate conditions show lower thermal insulation in compare with temperate climate. The green roof moisture exchange with the environment cause it to be more energy efficient than 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 greenery which it is small in winter. But there is a need for more researches exploring these aspects.

6.5. Integration factors

Intensive green roof has different thermal behavior in compare with extensive roofs. One reason is related to the fact that intensive green roof has more thickness and mass which cause more thermal inertia than extensive one 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 air flow. 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 one 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 roof can affect its thermal efficiency. Inverted roof would cause reduction of thermal efficiency of 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 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. Beside they have more mass which increase their thermal inertia.

7. CONCLUSION

Concluding generally the greenery would improve the thermal performance of building envelope and thus results in more energy efficiency so it helps energy saving.

- 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 would affect the thermal behavior of green envelope.
- Generally green envelopes improve the thermal function and energy performance of the 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 the roof layers materials would determine the thermal behavior of green roofs. But improving their function depends on climatic condition which determines the types of plants and type of integration of greenery into 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 compare with green roofs in different climates.

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[i] solar radiation beneath plants to the solar radiation hits the plants

[ii] percentage of the wall area covered by greenery

[iii] surface area of leaves within covering area

[iv] categorized to simple leaf, dissected leaf, and compound leaf

TABLES

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

Table 3. Thermal function of green roof layers which is mentioned in literature

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

Table 4. Green roofs impacts on the built environment in different scales which 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 impacts on the built environment in different scales which are derive 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

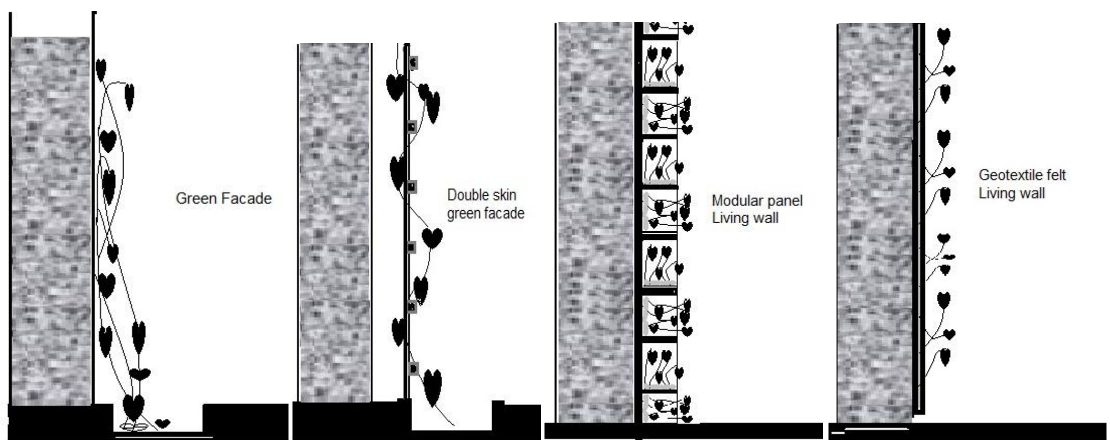

Figure 2. a) Green façade, the growth medium for plant is on the ground. b) Double skin green façade, an additional structure standing beside the wall supports the greenery. c) Modular panel living wall, the growth medium is in every box panel. d) Geotextile living wall, the growth medium is in the felt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

Figure 3. Green roof studies which is done so far considering climatic factors in different climates such as Arid, Tropical wet, Mediterranean, Humid subtropical, Marine west coast, Humid continental.

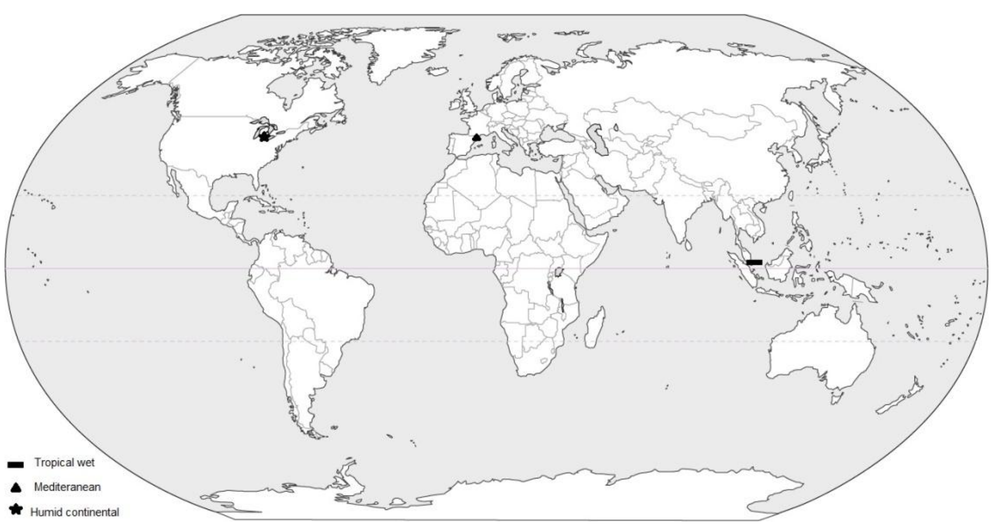

Figure 4. Green wall studies which is done so far considering climatic factors in different climates such as; Tropical wet, Mediterranean, Humid continental.