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Vertical Greenery Systems (VGS) for energy saving in buildings: A review

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ABSTRACT

This review paper organizes and summarizes the literature on Vertical Greenery Systems (VGS) when used as passive tool for energy savings in buildings. First, with the information obtained in the reviewed literature some key aspects to consider when working with VGS are clarified, such as the classification systems, the climate influence, the plant species used and the different operating mechanisms. Then, the main conclusions of this literature, sorted by construction system (Green Walls or Green Façades) and climatic situation, are summarized. In general, it can be concluded that VGS provide great potential in reducing energy consumption in buildings, especially in the cooling periods. However, a lack of data on operation during the heating period as well as during the whole year has been found. On the other hand, results show that the investigations of VGS are not equally distributed around the world, being basically concentrated in Europe and Asia. Moreover, the review concludes that some aspects must be studied in depth, such as which species are the most suitable for each climate, influence on energy savings of the façade orientation, foliage thickness, presence of air layers, and finally, substrate layer composition and thickness in the case of green walls.

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1. Introduction

In recent decades, the environmental consciousness increment has led towards using sustainability criteria in the urban systems and buildings design. Sustainable development requires the consideration of a whole host of interconnected elements, such as the reduction of energy demand and water consumption, minimizing waste and pollution and providing efficient public transport. Green space, including the greening of buildings, is just one piece of this jigsaw [1]. In that sustainable construction approach, the closing of materials and water cycles, and the reduction of energy consumption are priority objectives.

Recently, the concept of Green Infrastructure has been defined as a set of man-made elements which provide multiple environmental friendly functions at both building and urban scales. Among these functions, building energy savings as well as the reduction of ambient temperatures and mitigation of urban heat island effect stand out. In this regard, some of the most innovative and interesting solutions for this purpose are greenery construction systems for buildings, which are green roofs and green façades [2]. Thus, while traditionally greenery in architecture has been used primarily for aesthetic reasons, nowadays its use is also justified for ecological and economic reasons, such as energy savings, construction materials durability, urban climate improvement, support to biodiversity, etc.

However, vegetation is usually linked to drawbacks such as higher initial investment, maintenance costs, and possible damages to the building. Moreover, vegetation is variable along the time and the space (its shape, weight, foliage density, etc.), so that its advantages and disadvantages are neither immediate nor constant in time. This fact makes the quantification of its behaviour, and consequently it may compromise its implementation in buildings considering that engineers and architects need to control all the design variables, especially along the design phase.

There are basically two main ways to integrate vegetation into a building: green roofs and green façades. The use of green roofs is a fairly established practice around the world, with a clear classification between extensive and intensive systems, and abundant manufacturers. In contrast, in the case of vertical greenery of buildings, there is some dispersion regarding the constructive systems, the species used, etc. It should be noted that, from the architectural point of view, it is probably easier to use a flat space, the building roof, which has been recovered for people use due to the implementation of this green systems. In the case of green façades, the difficulty of its implementation on building vertical surfaces, and the fact that they are more visible from the street could be causes of its scarce use.

But on the other hand, greening the walls of a building has potentially more effect on the building environment than greening roofs, as the surface area of the walls of buildings is always greater than the area of the roof. With high-rise buildings this can be as big as 20 times the roof area [3].

Regarding greenery as a passive system for energy savings in buildings, there are some technical topics about its thermal behaviour and its main characteristics that have been addressed along the last years. Questions as the shading effect by plants, that is the capacity to intercept solar radiation, or the cooling effect by means of evapotranspiration from plants, are some of the main topics studied by researchers. But it is important to highlight that working with plants is not an easy matter and usually it is not possible to generalize the results of a study because of the weather conditions dependence, which influences plants growth, or on the plant species used (deciduous or perennial). Moreover, the differences between current systems, such as green façades or green walls, could lead to misinterpretation of research results.

This review paper organizes and summarizes the literature on Vertical Greenery Systems (VGS) as a passive tool for energy savings in buildings. First, with the information obtained in the reviewed literature some key aspects to consider when working with VGS are clarified, such as classification systems, climate influence, plant species used and different operating mechanisms. Later, the main conclusions of this literature, sorted by construction systems (Green Walls or Green Façades) and climatic situation, are summarized.

2. Key considerations

There are four key issues in the contribution of VGS on passive energy savings in buildings which could affect its operation that must be considered. First, the sort of construction system used to place plants on the building façades. Second, the climate influences not only the thermal behaviour of the building, but also the choice of plant species and how this climate influences their growth. Third, the type of plant species used, that is if they are deciduous or evergreen, shrub or climbing plants, etc. Finally, the last key aspect to consider is to know what mechanisms influence the operation of these green systems as a tool for passive energy savings.

2.1. Construction systems classification

According to Wong et al. [4], VGS involve any way to set plants in a building façade. Traditionally these systems consisted of climber plants that climb directly on the material façade. On a more updated approach, these systems tend to separate the plants from the façade surface in order to avoid potential problems associated with linking the building with living organisms. This implies the need to implement support structures to ensure the whole development of plants throughout the façade surface. With the aim of achieving this goal, different designs have been developed in recent years giving different construction systems.

Unlike other building systems, such as green roofs, in the case of green vertical systems there is no established standardization that determines its design and its variations. Thus, different researchers and enterprises have solved the challenge of covering large vertical building surfaces with plants, but at the same time, different designs also mean different thermal behaviours. This fact hinders the comparison between research results and makes it necessary to take into account the types of green systems when discussing these results.

In this regard Perez et al. [5] proposed a classification of VGS for buildings (Table 1). In this classification the authors differentiate these systems in extensive and intensive systems according to the requirements of implementation cost and further maintenance. On the other hand, this classification differentiates Green Vertical Systems into two big groups, the Green Façades and the Living Walls.

Table 1
Classification of Green Vertical Systems for buildings [5].

	Extensive systems		Intensive systems
Green façades	Traditional	–	–
	Double-skin	Modular trellis	–
		Wired	–
		Mesh	–
	–	–	Perimeter flowerpots
Living walls	–	–	Panels
	–	–	Geotextile felt

Green façades are VGS in which climbing plants or hanging port shrubs are developed using special support structures, mainly in a directed way, to cover the desired area. The plants can be planted directly in the ground, at the base of the structure, or in pots, at different heights of the façade. Green façades can be divided into three different systems [5]. *Traditional* green façades (Fig. 1), where climber plants use the façade material as a support; *double-skin* green façade or green curtain (Fig. 2), with the aim of creating a double-skin or green curtain separated from the wall; and *perimeter flowerpots* (Fig. 3), when hanging shrubs are planted around the building as a part of the composition of the façade to constitute a green curtain.

In the case of double skin green façades, the systems used are *modular trellises*, *wired*, and *mesh structures* [5]. *Modular trellises* are very light trellis metal modules mounted on the building wall or on independent structures, which become the support for climbing plants. In *wired structures* a system of steel cables, anchorages, separators, and other features are used to constitute a light structure that serves as support for climbing plants. *Mesh structure* consists of a very light structure that provides support for the climbers, made with a steel mesh anchored to the building wall or to the building structure.

Living walls are made of *geotextile felts* (Fig. 4) and/or *panels* (Fig. 5), sometimes pre-cultivated, which are fixed to a vertical support or on the wall structure [5]. The panels and geotextile felts provide support to the vegetation formed by upholstering plants, ferns, small shrubs, and perennial flowers, among others.

The classification proposed by Pérez et al. [5] incorporates and complements other classifications or system descriptions carried out by other authors as those that can be found in the Building Greener Guidance from CIRIA [6], Dunnet and Kingsbury [3], Kontoleon and Eumorfopoulou [7], and Ottelé [8].

2.2. Climate influence

When studying the potential of vegetation vertical systems for buildings as passive systems for energy savings in buildings, the

Fig. 1. Traditional Green Façade, Lleida, Spain.

Fig. 2. Double-skin Green Façade. Wired. Barcelona, Spain.

Fig. 3. Perimeter flowerpots Green Façade, Lleida, Spain.

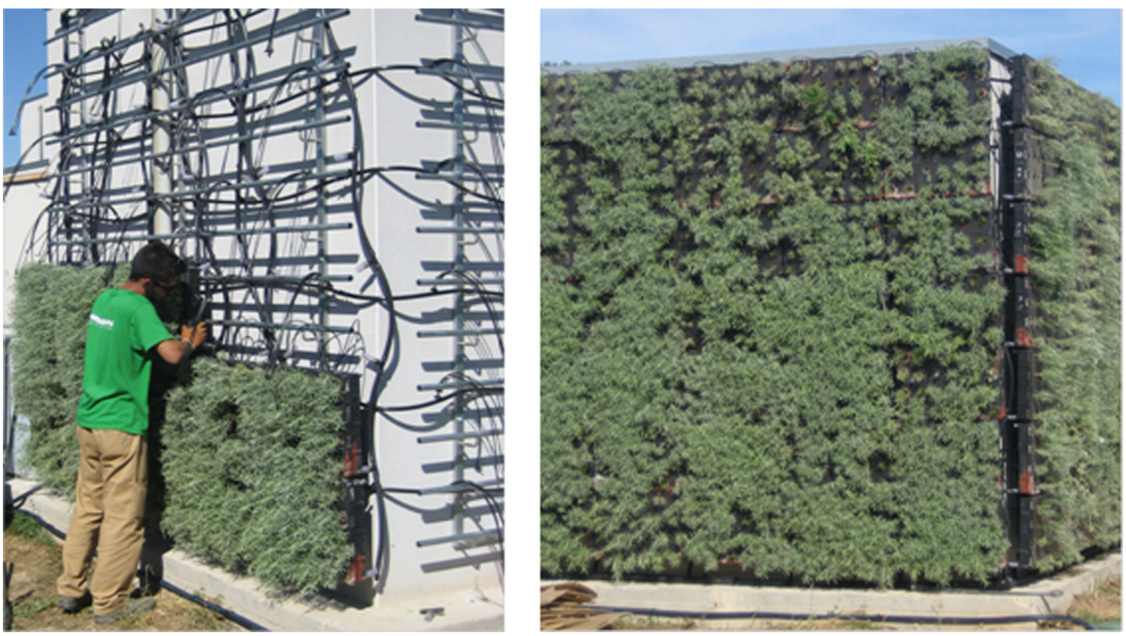


Fig. 4. Living walls. Panels. Puigverd de Lleida, Spain.

huge influence of weather conditions over their operation must be considered. In this sense, to the usual effect of climate on the thermal performance of a building, the effect of weather on the growth of plants (foliage density, plant height, etc.) and on their physiological responses (transpiration, position of leaves, etc.) must be considered too. Thus, the thermal behaviour of vertical greenery systems will also depend on weather conditions, which consequently will affect the results. Therefore, this variable must be considered when comparing these research results.

Often, authors do not specify the climate where the research took place. Other times they indicate it but without using a given known climate classification, thereby making comparison difficult. For this reason to compare the results of the main papers reviewed in this paper, it is considered appropriate to use the Köppen Climate Classification System [9], which is a widely used system for classifying the world's climates.

The Köppen Climate Classification categories are based on the annual and monthly temperature and precipitation averages. This system recognizes five major climatic types, designated by a capital letter: (A) equatorial, (B) arid, (C) warm temperate, (D) snow, and (E) polar. Within these types, different subcategories depending on the precipitation and temperature are defined (Fig. 6a and b).

In Tables 2, 4, 6 and 8 climates for the papers discussed in this review are specified, both according to the authors and according to the Köppen classification. Tables 2, 4, and 6 show the climatic classifications grouped according to the different climatic VGS, that is, Traditional Green Façades, Double-skin Green Façades and Green Walls, respectively. In these tables, the reviewed literature has been grouped according to its climatic similarities. Moreover, Table 8 shows the different studies related to simulations about VGS. In this table, studies have not been ordered by climatic similarity, because they usually used a wide variety of climates.

Considering the same climate classification facilitates a better interpretation of the results, which are summarized in Tables 3, 5, 7 and 9, and discussed in the following sections.

In Fig. 6b it can be seen that most of the papers found are located in the quadrant corresponding to the intersection of North and East hemispheres, leaving the entire Southern hemisphere

Fig. 5. Living walls. Geotextile felt, Madrid, Spain.

and Western hemisphere almost empty (only some simulation studies have been carried out with those climates). Regarding continents, most studies are concentrated in Europe and Asia, not having found studies in the other continents, America, Africa and Australia (apart from the aforementioned simulations). It can also be noted that most studies concerning Green façades are concentrated in Europe, while those referring to Green Walls are located mostly in Asia.

Moreover, considering that one of the main goals of these systems is the interception of solar radiation, it can be seen that there is a lack of studies in areas of the world with high solar radiation where these systems could be much more effective (Fig. 7).

Table 2 shows the classification from a climatic point of view for the studies about Traditional Green Façades. Only seven papers concerning this typology were found. As can be seen, studies were concentrated in areas with *warm temperate*; *fully humid*; *warm Summer* classification (Cfb), and one more was located in *warm temperate*; *fully humid*; *hot Summer* climate (Cfa). On the other hand, two studies were located in *snow* climate (D), both in *hot Summer* type, but one of these was *fully wet* (Dfa) type and the other *dry Winter* type (Dwa). Therefore, there are no studies located in arid (B) or equatorial (A) climates. In addition, there is a clear lack of studies located in *warm temperate* climate (C) but with stronger conditions for the summer, such as for example *Summer dry*; *hot Summer* (Csa) typology. Also, further studies in different variations of *snow* climate (D) should be conducted.

Table 4 shows the climatic classification for the ten studies found related to Green Double-skin Façades. In this case, the studies were located mainly in *warm temperate* climate (C), four of them with component *fully wet*; *warm Summer* (Cfb), three *fully wet*; *hot Summer* (Cfa) and two more were *Summer dry*; *hot Summer* (Csa). Moreover, only one study was found in *equatorial*; *fully humid* (Af) climate. Thus, in the case of Double-skin Green Façades, a lack of studies on *snow* (D) and *arid* (B) climates is found. In addition, an increase of the number of studies in *equatorial* climate (A) and other variables of warm temperate (C) climate would be necessary.

Table 6 shows the climatic classification for Green Walls systems. In this case eight studies were found, five of which were located in Asia. With respect to the climatic classification, six of them were located in *warm temperate* climate (C), covering a broad spectrum of variants since two of them were *fully wet*; *hot Summer* (Cfa), one more was *fully wet*; *warm Summer* (Cfb), two more *dry Winter*; *hot Summer* (Cwa), and finally one *Summer dry*; *warm Summer* (Csb). Moreover, two studies were located in *equatorial*; *fully humid* climate (Af). Again a lack of studies in *snow* (D) and *arid* (B) climates was found.

Table 8 shows the climates used in the simulation studies about VGS. A total of nine simulation studies involving up to 21 different locations were found. Four of them in *equatorial* climate (A), three in *arid* climate (B), six in *warm temperate* climate (C), and eight in *snow* climate (D), each with different variants within each climate. Although simulations studies allow more flexibility in order to work with different climates, an evident lack of studies in *equatorial* (A) and *arid* (B) climates was found.

Referring to Tables 2, 4, 6 and 8, notice the dispersion about the climate definition from different authors. Not only has there been dispersion in the nomenclature but even, there are studies in which climate classification was not even mentioned. As has been explained previously, climate influences significantly the plants' development and therefore affects the thermal behaviour of the green façades.

2.3. Plants species influence

Another aspect to consider in VGS when used as passive energy savings systems is the type of plants. Each constructive system uses different type of plants. Thus, in Green Façades climbing plants are usually used whereas in Green Walls shrubs and herbaceous plants are more common. Consequently, plants used for Green Façades can be deciduous or evergreen species, but in Green Walls plants are basically evergreen. This fact may have great importance in the façade's thermal behaviour. When using perennial plants both cooling and heating periods are influenced

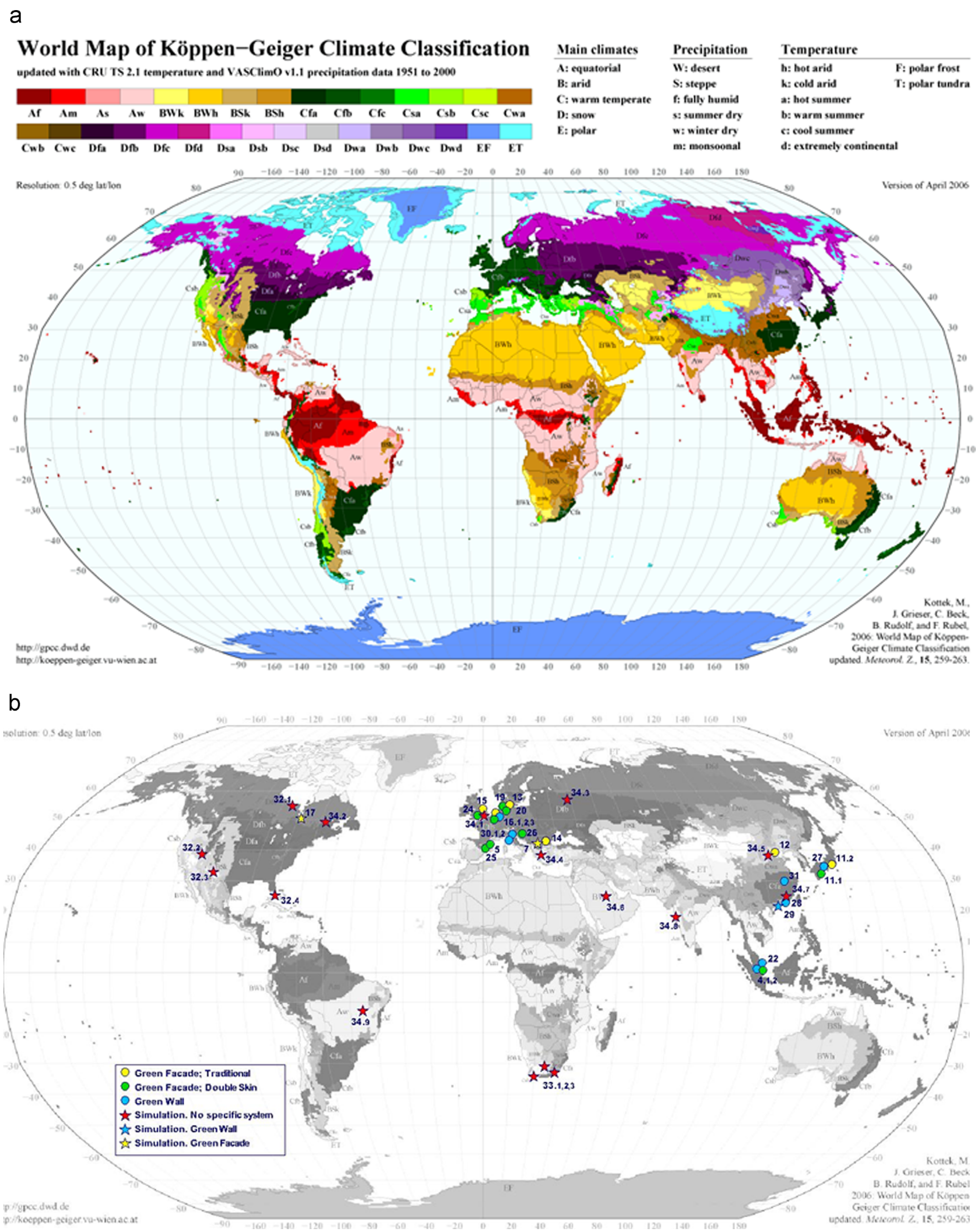


Fig. 6. (a) The Köppen Climate Classification, (b) The Köppen Climate Classification and situation of analysed papers by categories.

by plant coverage whereas using deciduous plants only the cooling period is affected since the solar radiation will pass during the heating period (leafless period).

On the other hand, according to Pérez [10] when working with deciduous plants the influence of solar gains in the building during the periods of transition, that is spring and autumn, must be also

Table 2
Climate classification. Green facades: Traditional.

Reference	Authors	Publication year	Location		Climate according to the author	Köppen classification	
11.2	Hoyano	1988	Japan	Tokyo	Temperate-humid subtropical climate	Cfa	**Warm temperate**; fully humid; hot summer
13	Köhler	2008	Germany	Berlin	–	Cfb	**Warm temperate**; fully humid; warm summer
14	Eumorfopoulou and Kontoleon	2009	Greece	Thessaloniki	–	Cfb	**Warm temperate**; fully humid; warm summer
15	Sternberg et al.	2010	England	Byland Abbey, Ramsey, Oxford, Nailsea, Dover	–	Cfb	**Warm temperate**; fully humid; warm summer
16.1	Perini et al.	2011	The Netherlands	Delft	–	Cfb	**Warm temperate**; fully humid; warm summer
12	Di and Wang	1999	China	Beijing	Humid continental climate	Dwa	**Snow**; winter dry; hot summer
17	Susorova et al.	2013	USA	Chicago	–	Dfa	**Snow;** fully humid; hot summer

Table 3
Green facades: Traditional, Related papers; Main characteristics and findings.

Reference	Köppen classification	Type of study	Period of study	Plant species	Orientation	Foliage thickness (cm)	Surface external building wall temperature reduction (°C)	Surface internal building wall temperature reduction (°C)
11.2	Cfa	Case study	Summer	*Parthenocissus tricuspidata*	West	–	13	11
13	Cfb	Case study	Summer/ winter	*Parthenocissus tricuspidata*	–	–	3 (summer) 3 (winter)	–
14	Cfb	Case study	Summer	*Parthenocissus tricuspidata*	East	25	5.7	0.9
15	Cfb	Case study	All year	*Hereda helix*	West-South	10–45	1.7–9.5	–
16.1	Cfb	Case study	Autumn	*Hereda helix*	North-West	20	1.2	–
12	Dwa	Case study/ simulation	Summer	*Hereda* sp.	West	10	16	–
17	Dfa	Simulation	Summer	*Parthenocissus tricuspidata*	South	–	7.9	2

Table 4
Climate classification. Green facades: Double skin.

Reference	Authors	Publication year	Location		Climate according to the author	Köppen classification	
11.1	Hoyano	1988	Japan	Kyushu	Temperate-Humid subtropical climate	Cfa	**Warm temperate**; fully humid; hot summer
26	Suklje et al.	2013	Slovenia?	Ljubljana?	–	Cfa/ Cfb	**Warm temperate**; fully humid; hot/warm summer
27	Koyama et al.	2013	Japan	Chikusa	–	Cfa	**Warm temperate**; fully humid; hot summer
19	Schmidt	2006	Germany	Berlin	Temperate oceanic climate (Cfb)	Cfb	**Warm temperate**; fully humid; warm summer
20	Wolter et al.	2009	Germany	Pillnitz, Dresden	–	Cfb	**Warm temperate**; fully humid; warm summer
24	Ip et al.	2010	England	Brighton	–	Cfb	**Warm temperate**; fully humid; warm summer
16.2	Perini et al.	2011	The Netherlands	Rotterdam	–	Cfb	**Warm temperate**; fully humid; warm summer
5	Pérez et al.	2011	Spain	Lleida	Mediterranean continental	Csa	**Warm temperate**; summer dry; hot summer
25	Pérez et al.	2011	Spain	Lleida	Mediterranean continental	Csa	**Warm temperate**; summer dry; hot summer
4.2	Wong et al.	2010	Singapore	Singapore	Tropical climate	Af	**Equatorial**; fully humid

taken into account. Leaves of different species grow at different moments and with different speeds during spring, and not all species lose their leaves at the same moment and according to the same speed during autumn.

Thus, given the importance of plant species used over the thermal behaviour of the building, and in order to know how the different authors have faced this issue, a list of the plants species used in the reviewed literature has been compiled, which is described in Tables 3, 5, 7 and 9 and is discussed below.

Table 3 shows the main characteristics of the reviewed literature about Traditional Green façades. Concerning the plant species used among the studies considered, it can be seen that indeed only two species were used, a perennial specie, ivy (*Hereda* sp.), and one evergreen specie, Boston ivy (*Parthenocissus tricuspidata*). Obviously both species have the ability to climb on the wall of the building without any additional support. Since the number of species of climbing plants that potentially can be used is very high, depending on the climate, it is clear that there is a gap in the choice of the most suitable species, which should be explored.

When considering the species used in Double-skin Façades studies (Table 5), an increase of species diversity is observed. This increment could be a consequence of the experimental purpose of most studies on Double-skin Façades. In this case, apart from ivy (*Hereda helix*) and Boston ivy (*Parthenocissus tricuspidata*), other interesting species such as Wisteria (*Wisteria* sp.) or Clematis (*Clematis* sp.), both of them deciduous plants, are found. This is

Table 5
Green facades. Double skin. Related papers; Main characteristics and findings.

Reference	Köppen classification	Type of study	Period of study	Plant species	Orientation	Foliage thickness (cm)/ coverage (%)	Air layer (cm)	Surface external building wall temperature reduction (°C)	Others
11.1	Cfa	Experiment	Summer	*Dishcloth gourd*	South-West	55%	–	1–3	–
26	Cfa/Cfb	Experiment	Summer	*Phaseolus vulgaris* "Anellino verde"	–	–	–	4	–
27	Cfa	Experiment	Summer	Bitter melon, Morning glory, Sword bean, Kudzu, Apios	South	54–52–29–52–15%	–	4.1–11.3–7.9–6.6–3.7	–
19	Cfb	Case study		*Wisteria* sp.	–	–	–	–	Evapotranspiration South face 5.4–11.3 mm/day (cooling value of 157 kWh/day)
20	Cfb	Experiment		*Hereda helix cv. woerner*	North, South, West, East	–	–	–	Leaf Area Index; LAI=7 (East)-8.51 (South)
24	Cfb	Experiment		*Parthenocissus quinquefolia*	South-West	–	–	–	Average solar transmissivity values of 0.45;0.31;0.27;0.22;0.12 for 1,2,3,4,5 leaf layers
16.2	Cfb	Case study	Autumn	*Hereda helix, Vitis, Clematis, Jasminum, Pyracantha*	–	10 cm	20	2.7	–
5	Csa	Case study	All year	*Wisteria sinensis*	South-East	20 cm	50–70	15.18	Air layer microclimate: Summer: -1.36 °C/+7%HR Winter: +3.8 °C/-8%HR
25	Csa	Experiment	Summer	*Parthenocissus tricuspidata, Lonicera japonica, Clematis* sp., *Hereda helix*	South	–	–	–	Maximum illuminance transmissivity coefficient: Parthenocissus 0.15, Lonicera 0.18, Clematis 0.41, Hereda 0.20
4.2	Af	Experiment	Winter	Experiment no. 2: climber plants	–	–	–	4.36	

Table 6
Climate classification: Green walls.

Reference	Authors	Publication year	Location		Climate according to the author	Köppen classification	
30.1	Mazzali et al.	2013	Italy	(A) Lonigo (B) Venezia	Mediterranean temperate	Cfa	**Warm temperate**; fully humid; hot summer
31	Chen et al.	2013	China	Wuhan	Hot and humid climate	Cfa	**Warm temperate**; fully humid; hot summer
16.3	Perini et al.	2011	The Netherlands	Benthnizen	–	Cfb	**Warm temperate**; fully humid; warm summer
28	Cheng et al.	2010	Hong Kong	–	–	Cwa	**Warm temperate**; winter dry; hot summer
29	Jim and He	2011	Hong Kong	–	–	Cwa	**Warm temperate**; winter dry; hot summer
30.2	Mazzali et al.	2013	Italy	(C) Pisa	Mediterranean temperate	Csb	**Warm temperate**; summer dry; warm summer
22	Wong et al.	2009	Singapore	Singapore	–	Af	**Equatorial**; fully humid
4.1	Wong et al.	2010	Singapore	Singapore	Tropical climate	Af	**Equatorial**; fully humid

because the creation of Double-skin Façades through support structures allows extending the use of the range of creepers, being possible to use all the species that use filiform tendrils, spines, etc., and other strategies in its vertical development. Furthermore, a group of species commonly used in agriculture for food production can be seen among the reviewed studies, such as dishcloth gourd (*Luffa* sp.), anellino verde (*Phaseolus vulgaris*), bitter melon, morning glory, etc.

Plant species used in Green Walls studies are listed in Table 7. For this system the situation is totally different from that for Green Façades because a number of different shrubs and herbaceous species can be used, even some creeper species. Consequently, species variability found was very large, and usually well-adapted local plants species were used for this purpose. Besides, many different species were usually used in the same Green Wall, making it even more difficult to obtain lists on specific species used in different climatic zones. In addition many authors do not provide the names of the species used. Since each single plant specie has its own characteristics that may influence the Green Wall thermal behaviour (shadow, evapotranspiration, etc.) the knowledge of what type of specie was used, its location in the Green Wall, the development degree, etc. must be key factors when designing these building systems.

Finally, in Table 9 plant species that have been considered in the simulation studies are specified. Some of these studies did not consider either the plant species or the constructive system used. Others studies, usually those who have made an experimental validation of the model used in the simulation, used similar species as the ones mentioned above depending on the construction system used (Traditional Green Façade, Double-skin Façade Green or Green Wall). However, it can be seen that many of these authors need to consider several assumptions about the plant properties due to lack of data (thermal conductivity, shading coefficient, etc.).

Although the number of plant species used until now is low, specially for Green Façades, interesting lists of possible plant

Table 7
Green walls. Related papers; Main characteristics and findings.

Reference	Köppen classification	Type of study	Period of study	Plant species	Orientation	Substrate type/ thickness (cm)	Foliage thickness (cm)/ coverage (%)	Air layer (cm)	Surface external building wall temperature reduction (°C)	Heat flux reduction (W/ m^2)	Others
30.1	Cfa	Experiment	Summer	Several, shrub, herbaceous and climber species	(A) South-West/ (B) South-West	Felt/1	–	(A) Open 5/ (B) Close 3	Day: (A)12–20; (B) 16/Night: (A) 2–3; (B) 6	(A) 70/(B) 1.5	–
31	Cfa	Experiment	Summer	Six different sp	West	Light substrate/10	–	Adjustable 3–60	20.8	2.5 (from building wall to air layer)	Air layer microclimate: Temperature reductions of 9.7 during day, and 1.6 during night, and 0.3% HR increment
16.3	Cfb	Case study	Autumn	Evergreen sp	West	Soil/22	10 cm	4	5	–	Wind speed reductions of 0.46 m/s in the air layer
28	Cwa	Experiment	Late Summer	*Zoysia japonica*	West	Hydroponic medium/ 7.5	64%	–	16	30 (from interior side building wall to indoor air)	–
29	Cwa	Simulation	–	*Euphorbia* × *lomi* “salmon”	South		–	15	8.83	–	–
30.2	Csb	Experiment	Autumn	Several, shrub, herbaceous and climber species	East	Soil/5	–	Open 5	Day: 12/Night: 3	–	–
22	Af	Simulation	–	*Nephrolepis exaltat/Urechites lutea/Ophiopogon japonicus/ Tradescantia spathacea*	–	10	% Variable	10	–	–	10–31% energy cooling load reductions
4.1	Af	Experiment	–	N3: *Hemigraphisrepanda*, N6: *Phyllanthus* myrtifolius, Tradescantia spathacea (N1, N4, N5, N7 moses, N8????)	–	Several (Table XX) -Soil substrate -Inorganic substrate - Green roof substrate	–	–	Day: 1 to 10.94/ Night 2 to 9 (depending on the system)	–	–

Table 8
Climate classification: Simulations.

Reference	Authors	Publication year	Location		Climate according to the author	Köppen classification	
32.1	McPherson et al.	1988	United States	Madison	Cold	Dfb	Snow; fully humid; warm summer
32.2	–	–	–	Salt Lake City	Temperate	Dsa	Snow; summer dry; hot summer
32.3	–	–	–	Tucson	Hot arid	BSh	Arid; steppe; hot arid
32.4	–	–	–	Miami	Hot humid	Aw	Equatorial; winter dry
33.1	Holm	1989	None (South Africa)	(Pretoria)	Hot arid	BWh	Arid; desert; hot arid
33.2	–	–	None		Hot humid	BSh	Arid; steppe; hot arid
33.3	–	–	None		Mediterranean	Csa	Warm temperate; summer dry; hot summer
12	Di and Wang	1999	Case study/ simulation	China	Humid continental climate	Dwa	Snow; winter dry; hot summer
18	Stec et al.	2005	Simulation/ experiment	None	None		
34.1	Alexandri and Jones	2008	United Kingdom	London	Temperate	CFb	Warm temperate; fully humid; warm summer
34.2.	–	–	Canada	Montreal	Subartic	Dfb	Snow; fully humid; warm summer
34.3	–	–	Russia	Moscow	Continental cool summer	Dfb/Dfc	Snow; fully humid; warm summer/cool summer
34.4	–	–	Greece	Athens	Mediterranean	Csa	Warm temperate; summer dry; hot summer
34.5	–	–	China	Beijing	Steppe (?)	Dwa	Snow; winter dry; hot summer
34.6	–	–	Saudi Arabia	Riyadh	Desert	Dwh	Snow; winter dry; hot arid
34.7	–	–	China	Hong Kong	Humid subtropical	Cwa	Warm temperate; winter dry; hot summer
34.8	–	–	India	Mumbai	Rain forest	Aw (Am)	Equatorial; winter dry/monsoonal
34.9	–	–	Brazil	Brasilia	Savanna	Aw	Equatorial; winter dry
22	Wong et al.	2009	Singapore	Singapore		Af	Equatorial; fully humid
7	Kontoleon and Eumorfopoulou	2010	Northern Greek region	–	Mild Mediterranean region	Cfb	Warm temperate; fully humid; warm summer
29	Jim and He	2011	Hong Kong	–	–	Cwa	Warm temperate; winter dry; hot summer
17	Susurova et al.	2013	USA	Chicago	None	Dfa	Snow fully humid; hot summer

species to use for VGS are provided in some of the books and Ph.D. thesis reviewed, such as Building Green [1], Dunnet and Kingsbury [3], or in Pérez [10].

2.4. Operating methods

Since VGS constructive systems are different (basically Green Walls or Green Façades) the mechanisms that regulate its thermal behaviour could also be different. Table 10 shows, in chronological order, the main research papers related to the use of VGS as passive tools in buildings for energy savings. The main effect investigated is also specified. Basically, four main effects should be considered: the shade effect, the cooling effect, the insulation effect, and the wind barrier effect [5]. Table 11 summarizes the definition of the operating methods of Vertical Green Systems as passive systems for energy savings in buildings.

The *shade effect*, which is probably the most significant for the energy savings purpose, consists basically of the solar radiation interception provided by plants. The majority of analysed studies have considered this effect.

The cooling effect takes place due to the water evapotranspiration process from the plants and substrates. Although half of the reviewed studies considered this effect, it is interesting to highlight that some of them did not consider actually the effect produced by water evapotranspiration. Instead of that, often the reduction surface temperatures of the wall's building façade due to the presence of plants are considered as cooling effect, without differentiating between shade and cooling effect.

Regarding the cooling effect, it should be mentioned that for Green Façades the only effect that really influences the thermal behaviour is transpiration from plants. This is closely linked to the type of plant species, the irrigation regime (the higher the irrigation quantity, the higher the transpiration ratio), and finally the orientation of the façade. As for Green Walls, in this case the water evaporation from the substrate should be added to the transpiration from plants, so that to the aforementioned variables for Green Façades the substrate moisture content must be added.

The Insulation effect is related to the insulation capacity of the different layers depending on the different systems composition, such as the substrate layer (thickness and materials), the air in the plant layer, other possible intermediate air layers, etc. Only five of the reviewed papers mentioned this effect and in all cases the effect was linked to the insulating effect due to the air layers, mostly linked to the Green Facades typology. In this regard, it is interesting to emphasize that some of the studies include the possibility of designing the façades with an interior air layer, which can be close or open, depending on whether the insulation effect should be prioritized or similar behaviour to a ventilated façade wants to be obtained, where the convection movement of air provides interesting advantages over the traditional façades.

Surprisingly, there are no studies about Green Walls analyzing in depth the insulating effect linked to the substrate layer. Therefore, this is a very important aspect to consider in future research.

Finally, the wind barrier effect refers to the capacity of VGS, which involves plants and support structures, to modify not only the direct wind effect over the building façade walls but also the air renovation in the different VGS layers, which influences the insulation capacity of this system indirectly. Only three studies actually considered this effect, and it was not always studied in depth. Therefore, further studies are necessary on this issue because of the relation between the effect of wind on the façades and energy losses.

Table 9
Simulations: Related papers; Main characteristics and findings.

Reference	Green vertical system		Plant species	Model/software	Parameters	Validation	Main assumptions
[32]		–	None	MICROPAS - SPS Shadow Pattern Simulation	Solar irradiance reductions/ Wind reductions/Energy performance of the building	No	Windows shading coefficient/air change rate/occupancy/uniform shade from plants
[33]	None	–	None	DEROB — Dynamic energy response of buildings	Indoor temperatures	4 days	Plants properties were not considered
[34]	None	–	*None*	Two-dimensional prognostic (dynamic) micro-scale model C++	Temperatures and energy savings	No	Properties of the plant
[12]	Green facade	Traditional	*Hereda* sp.	Mathematical model	Conductive heat transfer/ energy use reduction	2 summers	No overlap of the leaf layers/ Uniform leaf temperature/The ivy had negligible thermal capacity
[18]	Green facade	Double skin	*Hereda helix*	Simulink	Heat exchange between layers	Lab experiment	Properties of the plant
[7]	Green facade	Traditional	*Parthenocissus tricuspidata*	PCW — thermal-network model	Temperatures and energy savings	No	Plant thermal conductance
[17]	Green facade	Traditional	Boston ivy *Parthenocissus tricuspidata*	Mathematical model	Surface temperatures/Heat flux through the exterior wall	4 days	Leaf absorptivity coefficient, radiation attenuation coefficient, typical stomacal conductance, etc.
[22]	Green wall	Panels	*Nephrolepis exaltat/Urechites lutea/Ophiopogon japonicus/ Tradescantia spathacea*	TAS simulations	Temperatures and energy savings	No	Shading coefficient, greenery coverage
[29]	Green wall	–	*Euphorbia x lomi "salmon"*	Thermodynamics transmission model (TIM)	Heat flux transmission/ Temperature variations	12 days	Not explained

Reference	Main conclusions			
[32]	21% increment for heating in cold climates (great influence of South and East orientations)	53% reduction for cooling in warm climates (great influence of West orientation)	–	–
[33]	Indoor temperature: Maximum lowered by 4 K for arid climates	Indoor temperature: Minimum raised by 5 K for Mediterranean climates	–	–
[34]	The hotter and drier a climate is, the greater the effect of vegetation on urban temperatures	The larger amounts of solar radiation a surface receives, the larger its temperature decreases are when it is covered with vegetation	In hot climates, energy savings from 32% to 100% for cooling were calculated	–
[12]	Summer day peak-cooling load transferred through the wall was reduced by 28%	Heat gains reduction by solar radiation absorption: 40% of the energy absorbed by leaves is lost by convection, 42% by transpiration, and the rest by long-wave radiation to the environment	–	–
[18]	Temperature of each layer of the double skin façade was much lower for the case with plants than with blinds	For the same solar radiation, the temperature raise of the plant was about twice lower than for the blinds	Temperature of the plant never exceeded the temperature of 35 °C, when blinds could exceed 55 °C	Moreover, installation of plants in the double skin façade allows for reduction of the cooling capacity by almost 20%. A similar result was noticed for the energy consumption of the cooling system.
[7]	The exterior/interior surface reductions calculated were 1.73/0.65 °C for the North façade, 10.53/2.04 °C for the East façade, 6.46/1.06 °C for the South façade and 16.85/3.27 °C for the West façade	This effect implied cooling load reductions of 4.65% for the North, 18.17% for the East, 7.60% for the South and 20.08% for the West	–	–
[17]	On summer sunny days, a plant layer on a brick façade was estimated to reduce its exterior surface temperature by 0.7–13.1 °C	Heat flux through the exterior wall was reduced by 2–33 W/m^2	An effective *R*-value of 0.0–0.71 m^2 K/W was provided	–
[22]	The key behind shading is thicker greenery	Reductions between 10–31% energy cooling load were calculated due to the effect of greenery	–	–
[29]	South green walls had recorded reductions up to 8.83 °C	–	–	–

3. Vertical Greenery Systems for energy savings in buildings

In this section the literature on the use of VGS for energy savings in buildings is organized and summarized. According to previous considerations, papers have been organized into four sections to properly compare the results. First the literature relating to Green façades (Section 3.1), differentiating between Traditional (Section 3.1.1) and Double-Skin (Section 3.1.2), has been reviewed. Moreover the papers related to Green Walls have been grouped and summarized (Section 3.2). Finally, a section regarding simulations has been considered (Section 3.3). In order to facilitate a reading and interpretation of the results, the main features and conclusions of the reviewed papers are summarized in Tables 3, 5, 7 and 9.

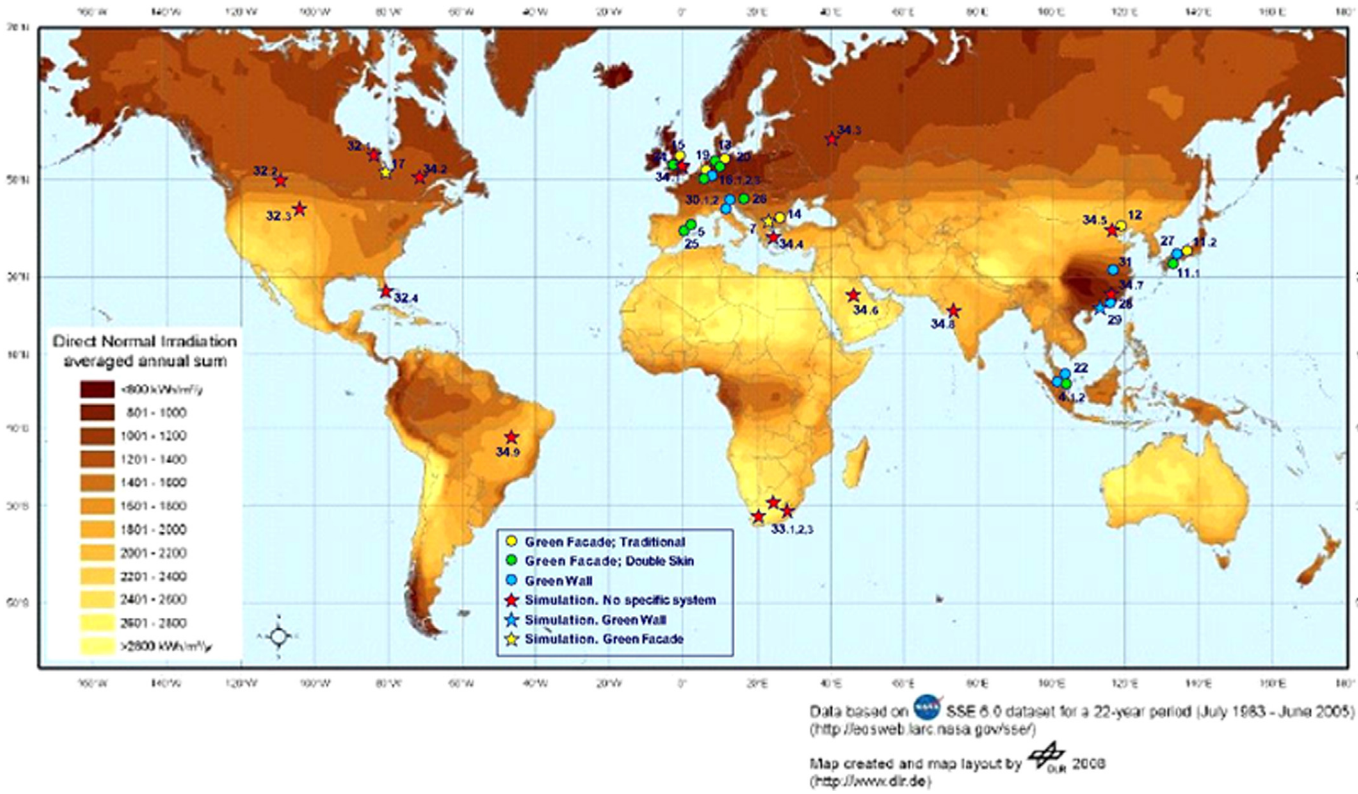


Fig. 7. Direct Normal Irradiation averaged annual sum and situation of analysed papers by categories.

Table 10
Operating methods. Related papers by year of publication.

Reference	Authors	Publication year	Green vertical system	Shade effect	Cooling effect	Insulation effect	Wind barrier effect
[11]	Hoyano	1988	Green façade. Traditional and Double skin	X			
[32]	McPherson et al.	1988	Simulation	X			X
[33]	Holm	1989	Simulation	X			
[12]	Di and Wang	1999	Simulation. Green façade. Traditional	X	X		
[18]	Stec et al.	2005	Simulation. Green façade. Double-skin		X		
[19]	Schmidt	2006	Green façade. Double skin		X		
[13]	Köhler	2008	Green façade. Traditional	X	X	X	
[34]	Alexandri and Jones	2008	Simulation	X	X		
[14]	Eumorfopoulou and Kontoleon	2009	Green façade. Traditional	X			
[22]	Wong et al.	2009	Simulation. Green Wall	X			
[20]	Wolter et al.	2009	Green façade. Double skin	X			
[4]	Wong et al.	2010	Green façade. Double skin/Green Wall	X	X		
[7]	Kontoleon and Eumorfopoulou	2010	Simulation. Green façade. Traditional	X		X	
[28]	Cheng et al.	2010	Green Wall		X		
[15]	Sternberg et al.	2010	Green façade. Traditional	X		X	
[24]	Ip et al.	2010	Green façade. Double skin	X			
[5]	Pérez et al.	2011	Green façade. Double skin	X		X	
[25]	Pérez et al.	2011	Green façade. Double skin	X		X	
[16]	Perini et al.	2011	Green façade. Traditional and Double-skin/ Green Wall	X			X
[29]	Jim and He	2011	Simulation. Green Wall	X			
[26]	Suklje et al.	2013	Green façade. Double skin	X	X		
[17]	Susurova et al.	2013	Simulation. Green façade. Traditional	X			X
[30]	Mazzali et al.	2013	Green Wall	X	X		
[31]	Chen et al.	2013	Green Wall	X	X		
[27]	Koyama et al.	2013	Green façade. Double skin	X	X		

3.1. Green façades

In this section the most important scientific contributions that have been made in recent years regarding the use of Green Façades (Traditional and Double-skin) as a passive system of energy savings are listed and summarized. For each author, the type of VGS, the plant species used, the climatic situation, the main parameters analysed, and the main conclusions have been

Table 11
Operating methods of Green Vertical Systems as passive systems for energy savings in buildings.

Effect	Method
Shade	Solar radiation interception provided by plants
Cooling	Evapotranspiration from plants and substrates
Insulation	Insulation capacity of the different construction system layers: plants, air, substrates, felts, panels, etc.
Wind barrier	Wind effect modification by plants and support structures

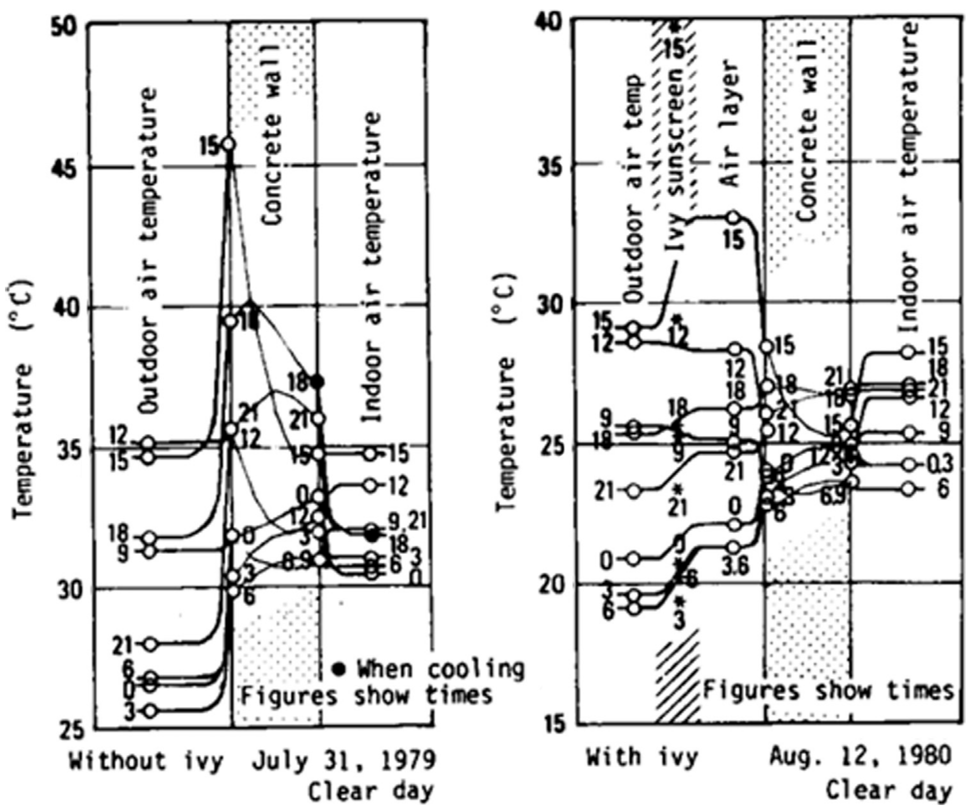


Fig. 8. Cross-sectional temperature distribution of the exterior walls, with and without ivy sunscreen [11].

described. Main features and conclusions of each paper have been summarized in tables in order to facilitate later interpretation (Tables 3 and 5).

Although three types of Green Façades have been defined (Table 1), Traditional, Double-skin and the Perimeter flowerpots, research literature related only to the first two types have been found. However, Perimeter flowerpots can also be interesting as a passive tool for energy savings in buildings by creating interesting sunscreens on the building façades.

3.1.1. *Traditional Green Façades*

Some authors have studied the operation of the Traditional green façades as thermal passive protection systems of the building. Generally speaking, Traditional Green Façades are made of creeper plants that climb on their own using the building façade wall material as support. In these systems climbing plants are usually placed at the base of the building façade walls and simple support systems adherent to the wall can be used.

Hoyano [11] studied the use of plants for solar control and how this effect influences the thermal environment of the building. One of the cases studied in this paper was the effect of a Traditional Green Façade made with Japanese ivy (*Parthenocissus tricuspidata*), located on the west side (15 cm thick bare reinforced concrete wall) of a two-story detached house in a residential district of Tokyo, during the summer season. In this study the exterior and interior building wall surface temperatures were measured. Due to the sunscreen effect of the green façade, reductions of up to 13 °C at 15 h in the external surface temperatures, and interior surface temperatures reductions up to 11 °C at 18 h were observed (Fig. 8). The calculated heat flow reduction through the outer surface of the building wall due to the sunscreen was a quarter (50 kcal/m^2 h) of the maximum value calculated without sunscreen (200 kcal/m^2 h), reducing to close to 0 kcal/m^2 h the heat flow that crossed the inside face of the building wall. Hoyano highlights the fact that during the night some air stagnation took place in the green screen that made the temperature increase in this space with a consequent negative effect on the convective cooling.

In this study, solar transmittance was defined as the ratio of the solar radiation on the building wall surface behind the ivy to that on the ivy sunscreen. Measured average solar transmittance was 2–7%.

Di and Wang [12] studied the cooling effect of a 10 cm thick Traditional Green Façade with ivy (*Hereda helix*) located on the South and West wall façades at the Tsinghua University Library of Beijing. The walls of this historic building are made of heavy brick. Measured parameters were solar radiation, temperature, heat flow, and wind speed. From these values the heat transfer through the walls was calculated with the following assumptions: there was no overlap between leaves, the temperature was uniform and ivy leaf had a negligible thermal capacity. The main results were that the mean temperature under the green cover was reduced by 8.2 °C compared to the temperature in front of the green façade. The maximum surface temperature reduction reached 16 °C at 4:40 pm. Theoretical calculations showed that the average solar radiation received during the day on the west-facing ivy-covered wall (189 W/m^2), 27.9 W/m^2 was reflected by the leaves, 133 W/m^2 was absorbed by the leaves, and 28 W/m^2 passed through the leaf layer. From the total solar radiation absorbed by the leaves, the average transpiration heat flux was 42%, 40% was lost by thermal convection, and 18% was lost by long-wave radiation to the wall.

Köhler [13], for the case of a traditional green façade in Berlin, stated that temperature differences under an ivy green façade (*Hereda helix*) can reach up to 3 °C at cold nights in winter (insulation effect), and up to 3 °C in summer (shade effect).

Eumorfopoulou and Kontoleon [14] conducted an experiment in order to assess the contribution of plant-covered walls to the thermal behaviour of building envelopes. Data were recorded in a 25 cm thick east-facing Traditional Green Façade (*Parthenocissus tricuspidata*), placed at the northern region of Greece (Thessaloniki) on a building with heat-insulated brick façade walls (masonry), whereas light-coloured plaster was used for both exterior and interior surface coatings. The measured parameters were the exterior and interior surface temperatures, the foliage temperature, and the external and internal environment temperatures. Furthermore, theoretical heat flows through the wall were calculated.

The main results showed that, due to the green coverage, the maximum daily temperature reduction on the east building wall was about 5.7 °C on the exterior surface and 0.9 °C on the interior surface of the wall. This reduction on surface temperatures implies an indoor temperature reduction of 0.5 °C with respect to the outside temperature in the case with green cover, being 0.4 °C for the bare wall.

Sternberg et al. [15] collected data, during a year, on temperature and relative humidity in five ivy Traditional Green Façades (*Hereda helix*) in various England locations. Differences between studied green façades were the foliage thickness and the orientation and exposure, according to Fig. 9. The results showed that across the five sites the average daily maximum temperature was 36% lower on ivy-covered façades than on exposed ones (shade effect). Furthermore, the daily minimum temperature was 15% higher on covered façade than on exposed ones (insulation effect). The ivy canopy reduced daily maximum surface temperatures significantly, ranging between 1.7 °C (< 10 cm thick ivy cover) and 9.5 °C (45 cm thick ivy cover). For the daily minimum surface temperatures the ivy canopy maintained temperatures between 0.64 °C (< 10 cm thick ivy cover) and 3.88 °C (20 cm thick ivy cover) higher than the exposed wall surface. Mean daily relative humidity at all the sites was slightly higher (but not significantly), between 1% and 15%, on ivy-covered than on exposed walls.

Perini et al. [16] studied the effect of airflow and temperature on the building envelope of different vertical greening systems.

Monitoring record for each site.

Site/ Location	Aspect	Dates recorded	Ivy canopy thickness (cm)	Exposure to light[a]
Byland	East	May 1, 2008–April 30, 2009	c. 20	High
Dover	East	May 1, 2008–April 30, 2009	c. 95	High
Nailsea	West	May 1, 2008–April 30, 2009	c. <10	Low
Oxford	South	May 1, 2008–April 30, 2009	c. 45	High
Ramsey	South	May 1, 2008–April 30, 2009	c. 24	Medium

[a] Exposure to sunlight without obstruction (building, trees) evaluated through repeated visual inspection.

Fig. 9. Traditional green façade features in Sternberg [15].

Among those, there was a traditional green façade, or direct façade greening according to the authors. It was a 20 cm thick ivy green façade (*Hereda helix*), with North-West orientation. The building façade was made with masonry material (clay bricks), which was located in an urban area of Delft (The Netherlands). The measured parameters were wind speed (1 m and 10 cm in front of the façade, in the middle of the foliage, and in the air cavity), the surface temperature, and the air temperature (1 m and 10 cm in front of the façade). Regarding wind speed no differences were found between 1 m and 10 m measurements in front of the façade. About surface temperatures, a reduction of 1.2 °C due to the effect of ivy was measured. These result values are small compared to others in similar studies because, according to the authors, the measurements were carried out in autumn without direct sun and with exterior surface temperatures lower than 18 °C. Referring to the wind speed, a reduction of 0.43 m/s within the foliage was measured in the case of the traditional green façade compared to the wind speed at 10 cm in front of the façade. Moreover, the wind velocity inside the foliage has the tendency to be nearly zero.

Susorova et al. [17] used data recorded in a Traditional Green Façade to validate a mathematic model to simulate the thermal performance of the vegetated exterior façades. Data collection took place over 3 days in a south façade at the Illinois Institute of Technology in Chicago, which had a composite structure of steel I-beam columns spaced 3 m, and metal frame windows occupying approximately 70% infill of the area and brick occupying approximately 30%. This part of brick façade was covered partially with Boston ivy (*Parthenicissus tricuspidata*). The measured parameters were the outdoor, exterior wall surface, leaf surface, and the interior wall surface, and within the foliage (5 cm from the wall façade) temperatures, relative humidity, wind speed and total horizontal solar radiation. The measurements showed that the highest difference between the bare and vegetated exterior surface temperatures occurred around 14:00 (7.9–5.7 °C), and agreed with the highest values of solar radiation measured. On the sunny day, the vegetated façade exterior surface temperature was consistently lower than that of the bare façade (mean difference of 1.6–1.1 °C) but it was approximately the same at night. The interior surface temperature of the vegetated façade was always lower than that of the bare façade (mean difference of 0.9 °C). From the simulation process the main conclusions were that solar radiation, façade orientation, and air temperature were more influential over the green façade thermal behaviour than the air relative humidity, wind speed or the plant parameters. The higher the solar radiation, the higher was the blockage by the vegetated façade. In terms of façade orientation, the plant layer is particularly effective in cooling the east and west façades that are exposed to the highest levels of solar radiation. Regarding the air temperature, at higher air temperatures, the façade plant layer was also less effective in cooling the façade exterior surface temperature and decreasing the heat flux through the façade. Increasing relative humidity also increased the reduction in surface temperatures, while by increasing wind speed, reductions in the surface temperature was lower due to the effect of the convection. Finally, in terms of specific parameters of the plant, the most influential were the Leaf Area Index (LAI) and the stomacal conductance. Usually the analysis showed that a plant layer with dense foliage (high leaf area index) and with leaves parallel to the wall (high attenuation coefficient values) is the most successful in reducing façade surface temperatures and heat flux through the façade.

In Table 3 previously analysed literature for Traditional Green Façades are organized according to their climatic classification. Besides, its main features and conclusions are shown, making it easier to compare similar studies. It can be seen that, in the case of the Traditional Green Façades, most studies are conducted using data collected on existing façades (old buildings, historical buildings, etc.). Furthermore, two of them are simulation studies in which data recorded in Traditional Green Façades were used to validate the model. Therefore, no experiment has been found in order to study this typology of façades. Referring to the duration, most studies limited the experimental study to summer period. Only a single study that considers the whole year was found, and only two more have data concerning the autumn and winter periods. Thus, more studies on the operation of the building system during winter, and transition periods (spring and autumn) are necessary. As for the plant species used, as has been mentioned above, only two species were used, a perennial one, ivy (*Hereda helix*), and other perennial, Boston ivy (*Parthenocissus tricuspidata*). Both species have autonomous growth mechanisms on the wall building material, without auxiliary structures. Thus, a deficiency in terms of number of different plant species used in Traditional Green façades is observed.

In terms of the main conclusions from the studies regarding energy savings, it has been considered that the most relevant parameter for comparison could be the registered reduction on the building's external wall surface temperature (°C) due to the effect of the green façade, because it is the first and most direct effect arising from the presence of sunscreen. In conjunction with this value, Table 3 provides, for each study, the façade orientation and the foliage thickness, as these two factors can be decisive in the obtained result. In view of these three values, the first general conclusion is that in all cases there was a reduction in the exterior surface temperature of the building wall, regardless of the façade orientation and foliage thickness. These reductions range from 1.7 °C to 13 °C on *warm temperate* climate (C) and between 7.9 and 16 °C in *snow* climate (D), in summer period in both cases. Also to emphasize that, from the cases analysed it could be concluded that west and east orientations have a big influence in the reductions during the cooling period. Furthermore, no differences between the contribution on energy savings from deciduous and evergreen species during the summer period was found. With this purpose, more studies about thermal behaviour during the whole year are necessary. As for the thickness foliage, the direct relationship with the energy savings is clear, and it can be stated that the higher the foliage thickness, the higher the reduction of the surface temperatures. In Table 3 data on the reduction of the interior surface temperature of the wall building façade has also been added. In all three studies that provide these data a reduction was measured, which verifies that green façades are a good tool for passive energy savings in buildings during the summer period. However, data related to the interior surface temperatures are not comparable because this value depends on the composition of each building façade wall. Sometimes, data on heat flux through the façade wall was also given, but again depend on the composition of the wall. Hence, a lack of studies for this purpose was found, so that they could be comparable, even varying the plant species, the façade orientation and the foliage thickness.

3.1.2. Double-skin Green Façades

In a more modern vertical greenery systems approach, the vegetation layer is separated from the building wall façade. Those new Double-skin Green Façade designs use pseudo-structures, mostly made of metal, for this purpose. Unlike the Traditional Green Façades, on which the climbing plants grow along the building wall façade without covering the windows holes, the new systems allow covering the façade according to a controlled way normally separated from the building wall, thanks to the light support structure. This implies that different degrees of coverage can be achieved, so that not only the opaque area of the wall but also the whole surface including the windows can be covered. In some cases, often experimental ones, only the windows are covered with plants.

In the experiment conducted by Hoyano [11] at the Kyushu University, the main objective was to measure the effect of a sunscreen (Dishcloth Gourd) in a South-West veranda as solar radiation control technique during summer periods. According to the author, although a veranda can be considered an attractive space to connect indoors and outdoors, its thermal environment can be degraded in summer by solar radiation affecting consequently the indoor climate. The measured parameters were the incident solar radiation, air temperature, globe temperature, relative humidity, leaf temperature, and the surface temperature in the veranda. It was found that the vine sunscreen was very effective for sun shading, reaching reductions of up to 60% on solar radiation when the solar altitude is low (after 15:00 h). This shade effect had a direct effect over air temperatures in the veranda, which were 1–3 °C lower with the sunscreen. Although the humidity of the veranda with the sunscreen was predicted to be higher than that without the screen, due to the transpiration of the leaves, no significant difference was found. In this study special emphasis was given to the negative effect of sunscreen over the cross ventilation. Cross ventilation, which is very necessary in summer time, went from 46% without screen to 17% with green screen.

Stec [18] conducted a lab experiment to evaluate theoretically (simulation) the shading effect by an ivy layer (*Hereda helix*) instead of the common blinds layer used in a Double-skin Green Façade. In this lab test facility it was found that the temperature of the cavity air behind the plants layer was significantly lower (20–35%) than behind the blinds layer. Moreover, in general the observed increase of the absolute humidity was in the range of 0.5–1.8 g/kg. Considering that the air temperature is increasing inside the cavity, the final relative humidity should not increase significantly.

Schmidt [19], talking about the Institute of Physics building at Humbolt University in Berlin-Adlershof, emphasizes the combination of a sustainable water management with the energy consumption reduction for cooling and ventilation. In this building, rainwater was used to supply a Double-skin Green Façade greening system and ventilation units. During summer 2005 the mean evapotranspiration for the south face of the building was between 5.4 and 11.3 mm/day, depending on which floor of the building the planters were located. This rate of evapotranspiration represents a mean cooling value of 157 kWh per day. According to the author, evapotranspiration is the most important factor of the environmental benefit of green roofs and green façades in urban areas. The evapotranspiration of a cubic metre of water consumes 680 kWh of heat. Hence, greening a building results in significant additional evapotranspiration. This fact has a high potential to reduce the building's surface temperatures and to improve the climate inside and around the building, especially in dry climates.

Wolter et al. [20] designed an experimental Double-skin Green Façade, made with steel trellis support and ivy plants (*Hereda helix*). Among other parameters, the authors studied the Leaf Area Index (LAI), well known in agriculture as one of the most representative variables of plant growth. Other authors, specially working with green roofs, have considered this index. According to Wolter et al. in the case of vertical greenery, the LAI describes a relation between the leaf area and the square metres of façade instead of the relation between the leaf area and the square metres of floor as usual (e.g. for green roofs applications). Moreover, it is necessary to take into account the fact that the LAI value changes with height in a green façade. Although Wolter's study does not consider the thermal benefits of green façades, as the LAI index has a direct influence on the foliage density this value can be linked to the thermal behaviour of green systems. The LAI average

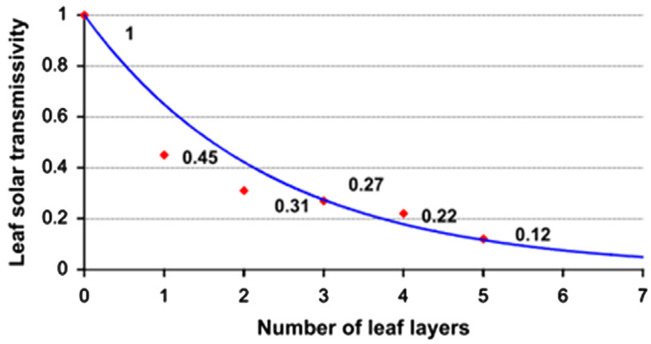


Fig. 10. Leaf solar transmissivity for different numbers of layers [24].

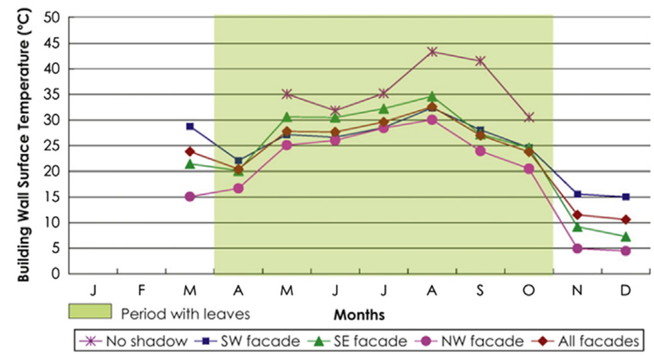


Fig. 11. Building wall surface temperature measured at the Golmés green façade, in 2009 [25].

measured at each exposition at the end of the testing period was between 7 (East) and 8.51 (South). These leaf area indexes lay in between or are even higher than those of conventional façade greenery with the *Hereda helix* (2.6–7.7). Other authors have considered LAI too in order to characterize the shade effect of green façades [17,21,22]. But by working with façades it is necessary to take into account that for vertical applications some adjustments must be done.

Furthermore, Wolter et al. [23] conducted an in-depth study of the potential of plants to intercept radiation. In this sense, the authors suggest using the Green Area Index against the Leaf Area Index, since the former takes into account all parts of the plant (also the rounded areas like leaf stalks and sprouts), and not just the projected leaf area as in the latter. The results showed that Green Area produces a 15% higher area compared to the sole consideration of the Leaf Area.

Wong et al. [4] conducted a large experiment in which data on the thermal behaviour of eight VGS in Singapore (tropical climate) were recorded. One of the eight systems was a Double-skin Green Façade made with modular trellis to support climbing plants (species unspecified). The measured parameters were the wall surface temperatures and the ambient temperatures in front of the façade. The average wall surface temperature reduction under the Double-skin Green Façade was 4.36 °C, maximum reductions being during the afternoon. According to this experiment, the VGS influence the ambient temperature was not significant.

In the Ip et al. [24] study, a coefficient that represents the shading performance of a climbing plant canopy over its annual growing and wilting cycle was proposed. The study was based on data from an experiment conducted during 2003 and 2004. In that experiment a Double-skin Green Façade, made with modular trellis and Virginia creeper (*Parthenocissus quinquefolia*), was placed in a window of an office building located in Brinhton (UK). The main measured parameters were temperature and relative humidity inside the office. Maximum reductions on indoor air temperature of 5.6 °C during the day and 3.5 °C during the summer nights (from July to September) in reference to the reference office without Green Façade on the window were observed. The relative humidity was also higher in the office window with the Double-skin Green Façade, about 4.7% higher in July to 13.7% higher in October.

A very interesting contribution of this study is the effort to characterize the shadow effect of Double-skin Green Façades. In this sense, the leaf solar transmissivity evolution depending on the number of leaf layers was characterized from up to 2000 measurements under the green façade (Fig. 10).

Pérez et al. [25] monitored for a year an existing Double-skin Green Façade located close to Lleida (Spain), under Mediterranean continental climate. The façade consists of a steel modular trellis support and Glycine climber plants (*Wisteria sinensis*). The measured parameters were exterior surface building wall temperatures, and exterior and intermediate space air temperatures, illuminance and relative humidity. Although illuminance instead of solar radiation was measured, this study showed that the shadow effect of Double-skin Green Façades is comparable to the best values of the shadow coefficient that usually can be obtained by using artificial barriers in buildings, such as slats, blinds and awnings. Understanding the Light Transmission Factor of the Double Green Façade as the ratio between the intermediate space illuminance and the exterior illuminance, this value ranged between 0.04 in July to 0.37 in April, during the season with the foliage fully developed. The exterior building wall surface temperature in a covered area was 5.5 °C lower than in an exposed area. This difference was higher in August and September, reaching maximum values of 15.2 °C on the South-West façade in September (Fig. 11). The air in the intermediate space changed, creating a microclimate where environmental conditions were higher temperature and lower relative humidity in winter (leafless period), and lower temperature and higher humidity in summer (period with leaves). This fact verified the Double-skin Green Façade wind barrier effect and the evapotranspiration effect of the plants as well.

In order to determine the transmission capacity of four different plant species well adapted to this climate, a simple experiment was carried out [25]. The species chosen were ivy (*Hereda helix*) and honeysuckle (*Lonicera japonica*), as perennial plants, and virginia creeper (*Parthenocissus quinquefolia*) and clematis (*Clematis* sp.), as deciduous plants. In the field of construction, the shade factor is the fraction of solar radiation incident on an opening of the building that is not blocked by the presence of obstacles such as blinds, awnings, and slats. Therefore, the light transmission factor has to be considered as an approximation to this shade factor, that is, the relationship between the illuminance behind the obstacle and the illuminance in front of the obstacle. The results of this experiment showed light transmission factor values of 0.15 for Virginia creeper, 0.18 for honeysuckle, 0.14 for clematis and 0.20 for ivy plants. These values, as occur in the other work [5], are comparable to the best values of the shadow factor that can be obtained using artificial barriers for the south orientation.

In Pérez [10] the importance of using deciduous species in the regulation of solar gains along the different seasons of the year was considered. Conclusions highlight the importance of knowing the biological cycle of different species under different climates, because this influences the moment when leaves will fall (or grow) and therefore what amount of solar gains could be considered for the thermal balance of the building. This is particularly important in the transition seasons, that is, spring (when the leaves grow) and autumn (when the leaves fall).

In the Perini et al. [16] study about the effect on airflow and temperature on the building envelope of different vertical greening systems a Double-skin Green Façade located in Rotterdam (The

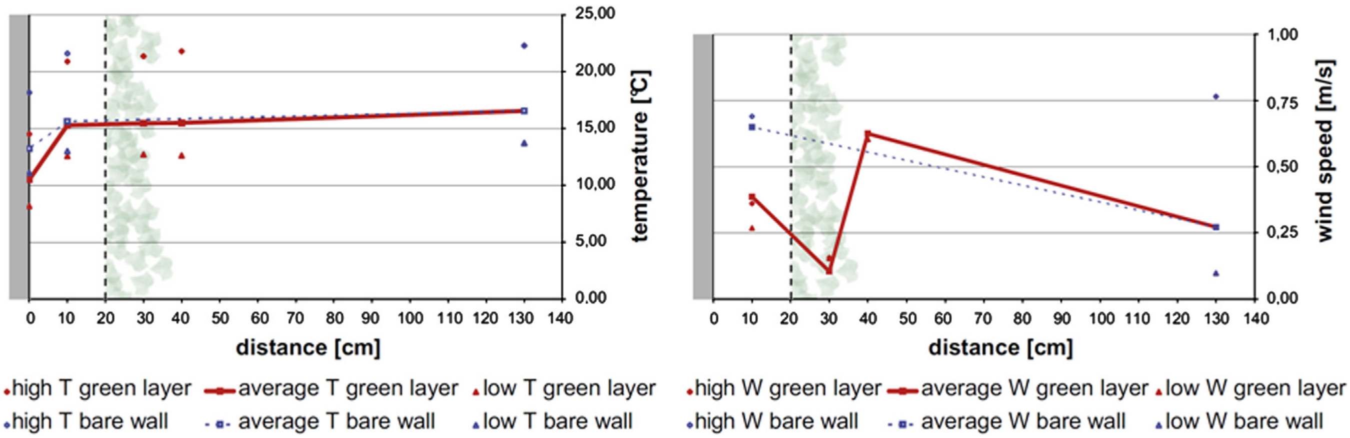


Fig. 12. Indirect façade greenery, temperature (left) and wind speed (right) profiles [16].

Netherlands) was analysed. The façade was made with aluminium pots placed at several heights and steel frames where different species of climbing plants, such as *Hereda* sp., *Vitis* sp., *Clematis* sp., and *Jasminum* sp., and some shrubs as *Pyracantha* sp., could grow. The façade, which had North-East orientation, was not completely covered at the time of the study and there was a 20 cm thick air cavity between the building façade and the plants layer. The measured parameters were the wind speed (1 m and 10 cm in front of the façade, within the foliage, and in the air cavity), the external building wall surface temperature, and the air temperature (1 m and 10 cm in front of the façade). About the wind speed no differences were found between 1 m and 10 cm in front of the façade measurements. Regarding the external building wall surface temperatures reductions of 2.7 °C were measured (Fig. 12). As it is mentioned previously for the Traditional Green Façade, in this study these result values are small compared with others in similar studies because, according to the authors, measurements were carried out in autumn without direct sun and with exterior surface temperatures lower than 18 °C. Referring to the wind speed a reduction of 0.55 m/s inside the foliage was measured in the Double-skin Green Façade, whereas only 0.29 m/s wind speed reduction was measured in the air cavity (20 cm thick), compared to the wind speed at 10 cm in front of the façade.

Suklje et al. [26] conducted an experimental study on a microclimatic layer of a bionic façade inspired by vertical greenery. In this study a Double-skin Green Façade, made with wire mesh and Anellino Verde (*Phaseolus vulgaris*) plants, was used in order to compare its thermal behaviour with the behaviour of the artificial design proposed by the authors. In the measurements, the wall surface temperature under the green façade was up to 4 °C lower than the black façade. In this paper results related to the analysis of conditions were very interesting because the authors concluded that the foliage temperature increases according to a lineal relation with the ambient temperature, whereas foliage temperature increases with the solar radiation, but without following any rule. Finally, temperature in the microclimate layer does not depend on the wind speed.

Koyama et al. [27] made a study about the identification of key traits contributing to the cooling effects of green façades. This study took place in Chicusa (Japan) using five climbing plants located on freestanding walls oriented to the south. Plant species used were bitter melon (*Momordica charantia*), morning glory (*Ipomoea tricolor*), sword bean (*Canavalia gladiata*), kudzu (*Pueraria lobata*), and apios (*Apios American medikus*). The experiment was performed during summer 2008, and the measured environmental parameters were the environmental temperature and relative humidity, the global solar radiation (south, vertical and horizontal), and the photosynthetically active radiation (Fig. 13).

Fig. 13. Six freestanding walls, five of which were covered by five different vine plant species that were trained to climb the plastic nets while one wall was not covered to serve as a black control [27].

In the panels, wall surface temperature was measured, and about the related plant trait parameters, the longest vine length, total number of leaves, leaf coverage percentage, leaf surface temperature, leaf transpiration rate, and leaf solar transmittance were measured. In the conclusions, significantly positive relationships between the percentage coverage and the temperature reduction under the green screens were found, ranging from 3.7 °C to 11.3 °C, on average, with coverage between 15% and 54%. According to the authors, the coverage percentage and the solar radiation are the most influential parameters over the surface temperature reductions. Moreover, no reduction was observed when the global solar radiation was lower than 0.1 kW/m^2. As this fact occurred usually during evening and night periods, it can be deduced that green façades had the potential to increase the wall surface temperature during the night through blocking long wave radiation from the walls to the environment.

In Table 5 the previously reviewed studies about Double-skin Green Façades are organized by climatic classification and its main features and conclusions are shown. In reference to the typology of study it can be seen that seven of the ten papers analysed were experiments and only three were studies concerning real cases. This fact evidences that Double-skin Green Façades are contemporary constructive systems, very interesting to the scientific community for its potential as a passive energy savings system in buildings. All reviewed studies, except one, were located in *warm temperate* climate (C). Six of them considered only the summer period, only one of them considered the whole year, and another one took place during the autumn period. Regarding the study located in *equatorial fully humid* (Af) climate, winter period was considered and therefore the fact that temperatures are between 29 and 30 °C and weather is rainy should be taken into account. In terms of façade orientation, south orientation was the most used. Hence, there is a lack of consistent data regarding the contribution of the different orientations in energy savings provided by the green curtains.

In the same way as was done for the Traditional Green Façades, the parameter that is considered more appropriate for comparing different studies was the reduction on the external surface temperature of the building façade wall (°C), also considering the façade orientation, the foliage thickness (cm) or the percentage of coverage (%), as well as the thickness of the air layer between the Double-skin Green Façade and the building façade wall in centimetres. In this regard, for warm temperate climates (C) a reduction in the external surface temperature of the building wall façade ranging from 1 °C to 15.18 °C was observed, and in the study located in equatorial climate (A), the reduction was 4.36 °C. It can be seen that the number of studies with clear results was too scarce to be compared properly and to achieve a clear conclusion about the level of energy savings that these systems can offer. In reference to the coverage degree, it should be emphasized that the maximum external temperature building wall reduction (15.18 °C) took place with a high degree of coverage and with a foliage thickness of up to 20 cm. Nevertheless data are too sparse to draw a clear conclusion about the façade orientation and the foliage (coverage percentage and thickness) influence over the final results.

A very interesting issue is the cooling effect due to the evapotranspiration from plants, but it was only calculated in one study [19]. Therefore it is necessary to further discuss this point which can significantly influence the thermal behaviour of these constructive systems.

It is also remarkable the analysis carried out one in some papers about the microclimatic conditions that occur in the intermediate air layer between the building façade wall and the green façade, where a variation in humidity, temperature and wind speed seems to take place, creating a microclimate that can significantly influence the whole façade thermal behaviour [5,16,25]. In addition, the existence of this intermediate air layer links the operation of Double-skin Green Façades with current ventilated façades [18]. This is a very important topic to study in depth on future research about Double-skin Green Façades.

Finally, three studies deal with the shadow effect produced by green curtains, either making an attempt to calculate directly the ability of interception of solar radiation by plants, or using the Leaf Area Index (LAI), which has been traditionally used in agriculture to measure the density of crops and it is linked to aspects such as the growth and yield of crops [20,21,23]. Thus, the use of LAI as a representative value of the potential of VGS for energy savings and for comparing different experiments may become of great interest. However, it should clearly specify how it must be used, because LAI was designed to be used with crops and therefore its calculation is done in a horizontal way whereas for VGS a vertical calculation is necessary. Therefore, appropriate adjustments about LAI calculation, as a measure of foliage density and consequently about the solar radiation interception potential must be provided in future research. Some simulation studies assume a value for the LAI index in order to describe the level of interception of solar radiation [17,22].

3.2. Green walls

In this section the literature relating to Green Walls as a passive tool for energy savings in buildings is reviewed. The system construction, the plant species used, the climatic situation, the main parameters analysed and the main conclusions for the different papers found is organized and summarized. Main characteristics and conclusions of each paper have been summarized in Table 7 in order to facilitate the interpretation of results.

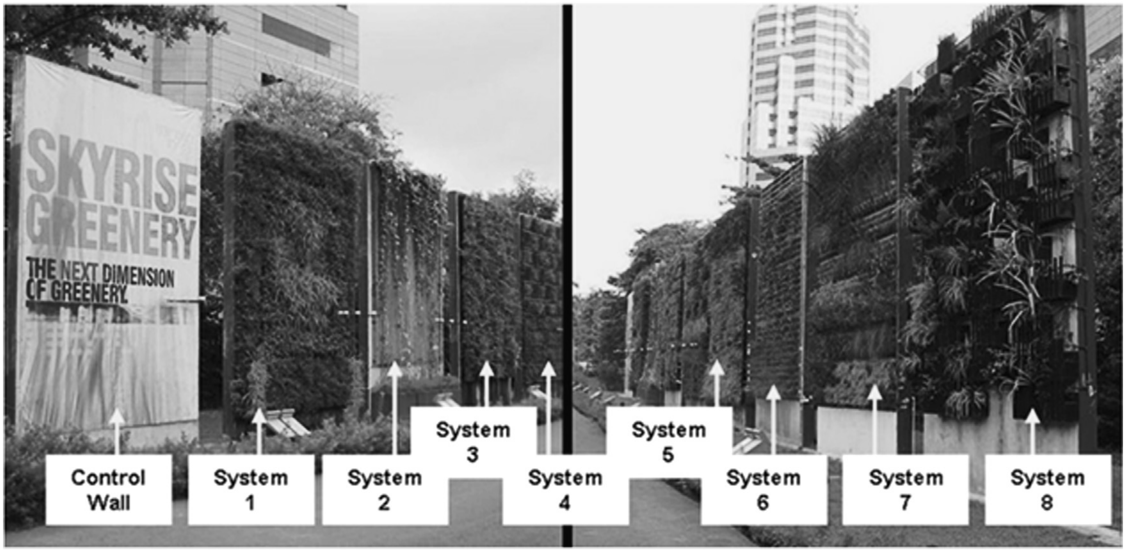
Considering the Vertical Greenery Systems classification from Table 1, there are two main types of Green Walls, the Geotextile felt green walls, where plants are supported by a continuous geotextile felt, usually without using substrate, and Panels green walls, where plants are located in different sort of panels, made with plastic, metal or other materials, filled with substrate. The fact that only few studies related to Geotextile green walls have been found must be taken into account. The reason for this lack of research could be because these systems are related to an intensive gardening practice, with a strong artistic component, far away from the objectives of energy savings and sustainability approach.

Wong et al. [22] simulated the effects of vertical greenery systems on the temperature and energy consumption of buildings. For these simulations different plant coverage to a hypothetical building was given. Referring to weather, data for 2001 in Singapore was taken into account. In this work the influence of shadow effect over energy consumption reductions for refrigeration (energy cooling load) was calculated theoretically. One of the main conclusions was that the shadow effect is closely related to the density of the foliage, which was related to the LAI of the fern species used (Boston Fern (*Nephrolepis exaltata*)). As it was a theoretical work, the authors did not specify any particular building system. Although according to the species and the substrate layer used on the calculations suggest that the authors were considering a Green Wall constructive system. In the conclusions, it was found that the key behind shading is thicker greenery. Moreover, reductions between 10% and 31% energy cooling load were calculated due to the effect of greenery.

Later on, Wong et al. [4] conducted an experiment in which data on the thermal behaviour of eight Vertical Greenery Systems (VGS) in Singapore (tropical climate) was recorded. Among these, seven were Green Walls with different construction characteristics (Fig. 14a and b). The measured parameters were the surface temperatures of the wall below and the air temperatures in front of the green wall. The results showed that, in terms of average wall surface temperature reduction, VGS 4 and 3 appeared to have the best cooling efficiency during the day, reaching a maximum temperature reduction of more than 10 °C. This was followed by VGS 1, 5 and 8 where the maximum average wall surface temperature reduction ranges from 8 °C to 10 °C, and finally VGS 6 and 7a, both achieved a slightly lower maximum wall surface temperature reduction of around 6 °C. For substrate surface temperature reduction, VGS 3, 4 and 5 show the best capacity, reaching beyond 8 °C, followed by VGS 8 and 1, ranging between 6 °C and 8 °C. Finally, VGS 7 and 6 had the least performance where reductions were below 6 °C and there were several occasions where the average substrate temperatures indeed exceed the control wall temperature. On the other hand, according to this experiment it can be stated that VGS do not influence significantly the surrounding ambient temperatures.

Cheng et al. [28] conducted an experiment of a green wall consisting on aluminium modules with slabs of hydroponic medium where a warm-season grass (*Zoysia japonica*) was established. The objective of the study was to determine the thermal performance, in the late summer period when the weather remained hot and dry. The studied parameters were vegetation cover, moisture distribution along the vertical profile, drainage from the panels, temperature difference between the substrate, and the ambient air (cooling effect), heat flux and power consumption. Results showed strong associations between moisture in the growth medium, vegetation coverage and cooling effect.

a



b

VGS	System typology	Description	Plant size
1	Living wall – Modular panel, vertical interface, mixed substrate	Combination of 2 systems: the versicell-based and 'plug-in' slot planter system. Versicell planters have drainage cells with selected mixture of green roof and soil planting media wrapped in geo-textile membrane while the slotted planters are mainly planter cages system.	Small to medium
2	Green façade – Modular trellis	Climber plants in planters forming green screens across mesh panels on the wall.	Climber plants
3	Living wall – Grid and modular, vertical interface, mixed substrate	Plant panels embedded within stainless steel mesh panels inserted into fitting frames.	Small
4	Living wall – Modular panel, vertical interface, inorganic substrate	Employed the Parabienta system with a patented growing medium (composite peat moss) as a planting media inlay. The peat moss panel encased in a stainless steel cage is hung onto supports lined with integrated irrigation.	Small
5	Living wall – Planter panel, angled interface, green roof substrate	This system uses a UV-treated plastic as a molded base panel with integrated horizontal planting bays.	Small
6	Living wall – Framed mini planters, horizontal interface, soil substrate	Individual mini planters placed and secured onto stainless steel frame.	Small
7	Living wall – Vertical moss-tile, vertical interface, inorganic substrate	Patented ceramic tiles shipped with pre-grown moss species. Suitable for creating tiling designs	Small, custom-grown on tiles
7a	Living wall – Flexible mat tapestry, horizontal interface, soil substrate	Lightweight panel comprising 2 layers of moisture retention mats secured onto a supporting grating or mesh. Plants slotted and pre-grown in between mats. Suitable for flat and curved surfaces. Allows ease of change.	Small to medium
8	Living wall – Plant cassette, horizontal interface, soil substrate	Use of planters to hold wider variety of plant types and of larger sizes. Planters are secured onto the wall through hinges. Lightweight growing medium is used.	Small to medium-large

Fig. 14. (a) Picture of vertical greenery systems in HortPark [4]. (b) Description of vertical greenery systems in HortPark [4].

Green panels not only reduced solar heat transfer to the wall, but also kept the wall warm at midnight by buffering and delaying the heat transfer through the façade wall. Heat flux of the bare wall showed peaks that exceed 40 W/m^2 in the afternoon, while in the presence of vegetated panels the heat flux only fluctuated below 10 W/m^2. Lower heat inflow reduced significantly the daily power consumption by 1.45–1.85 kWh in a small room of 9.35 m^3 behind the green wall.

In Perini et al. [16] the effect on air flow and temperature on the building envelope of different vertical greening systems was studied. About Green Wall systems, the case studied was placed in Benthuizen (The Netherlands), and the wall was made with plastic modules (HDPE) filled with soil (22 cm thickness) and planted with different evergreen plant species ($\pm$10 cm thickness). The building material façade was plywood, and there was a 4 cm air cavity between the façade and the planter boxes. The measured parameters were wind speed (1 m and 10 cm in front of the façade, within the foliage, and in the air cavity), the external building wall surface temperature, and the air temperature (1 m and 10 cm in front of the façade). About wind speed, no differences were found between 1 m and 10 cm in front of the façade measurements. For the surface temperatures of the wall façade there was a hypothetical calculated reduction of 5 °C, these reductions being of 1.1 °C in the air cavity. As was mentioned previously for the Traditional Green Façade and for the Double-skin Façade studied, in this study the result values are smaller compared to others in similar studies because, according to the authors, measurements were carried out in autumn without direct sun and with exterior surface temperatures lower than 18 °C. Referring to the wind speed measurements, the wind velocity profile for the Green Wall system shows a decrease from 0.56 m/s to 0.10 m/s starting from 10 cm in front of the façade to the air cavity (based on a hypothetical wind velocity for a bare wall situation).

Jim and He [29] conducted an experiment to validate the simulation done about the estimation of the heat flux transmission of vertical greenery ecosystems. In this experiment, results showed that when global solar radiation and temperature of the south control wall had reached maximum values, the south green walls had recorded reductions of up to 8.83 °C.

Mazzali et al. [30] conducted an experimental investigation on the energy performance of living walls in a temperate climate. The study took place in Northern and central Italy. Three different experimental Green Walls, located in Lonigo, Venezia and Pisa,

Fig. 15. Thermal labs with the Living Wall System (LWS) on the roof [31].

were made using several shrubs, grasses, and climber plant species. The recorded parameters were surface temperatures, external air temperatures and relative humidity, air velocity, heat flux and solar radiation. Main results were surface temperature reductions between 12 and 20 °C during sunny days, and increments of about 2 °C during nighttime, for the Green wall placed in Lonigo. These results showed that the bare wall will tend to cool itself more than the covered wall during nighttime. For the heat flux measured, the difference between heat fluxes outgoing from the wall behind the living wall (18–30 W/m^2) compared from a bare wall (90–100 W/m^2) was in the order of 70–80%. For the green wall located in Venezia, the reduction on the external surface temperatures was 16 °C during daytime, and the increment at night was about 6 °C. The incoming heat flux was 6–9.7 W/m^2 for the green wall while it ranged from 6.2 to 11.2 W/m^2 for the bare wall. Finally, the values for the living wall placed in Pisa were external surface temperature reductions of 12 °C during the day, and increments of about 3 °C at night. On the whole, it can be concluded that the prevalence of outgoing heat fluxes has a significant advantage during the summer season because it represents a clear reduction of the cooling load supplied by the HVAC system with a direct reduction in the primary cooling energy consumptions.

Chen et al. [31] carried out an experimental evaluation of a living wall system in hot and humid climate. The experimental green wall was placed in Wuhan, China. Six different plant species were used, and the main parameters were the interior, interior wall surface, exterior wall surface, air gap, interior back panels surface and exterior temperatures, the interior, air gap and exterior relative humidity, the wind speed and the solar radiation (Fig. 15). The main conclusions were exterior wall surface temperature reductions of 20.8 °C, interior wall surface temperature reductions of 7.7 °C, and indoor temperature reductions of 1.1 °C. In the air gap between the building façade and the green wall reductions of 9.7 °C during day and 1.6 °C during night were found. The calculated heat flux from the exterior wall surface from the air gap was 2.5 W/m^2, and the calculated energy saving, with a set point of 24 °C, was around 0.4 kWh. The mean relative humidity in the air gap was 0.3% higher than the exterior relative humidity. According to the authors, a sealed air layer in the air gap performs better in its cooling ability than a naturally ventilated air layer. Moreover, a smaller air gap distance between the façade building and the green wall performs better as well.

In Table 7 reviews the literature on Green Walls organized by climatic classification and main features and conclusions are shown. Of the eight studies analysed, five were experiments, two were simulations and only one was an analysis of a real case. In this regard, as with the Double-skin Green Façades, it can be deduced that Green Walls are emerging systems, currently on development process, with a huge potential from the point of view of energy savings and sustainability and therefore of big interest to the scientific community. Reviewed studies about Green Walls were located mainly in *warm temperate* (C) climate, although two of them were located in *equatorial* climate (A). The experiments were carried out mainly during summer and autumn periods, and there is a data gap regarding the winter period and the whole year. As for the plant species, as has been mentioned in previous sections, in the case of Green Walls the range of species used is very high because the system can work with several shrubs and grass species, even with climbing plants. Generally species used for Green Walls are usually well adapted to the climatic conditions of each location. What is missing along the research reviewed studies is perhaps a better understanding of the potential of each species on providing shade, foliage density, evapotranspiration capacity, etc. in order to link directly these species to particular energy savings. In the same way as in the previous cases, the most appropriate parameter to compare different studies is the reduction on the exterior surface temperature of the building façade wall (°C), since this parameter can be found in many of the analysed papers and it is representative of the potential energy savings provided by the green system. Together with this parameter and with the aim to facilitate the results interpretation, five more parameters have been included in Table 7 such as façade orientation, substrate typology, substrate layer thickness, foliage thickness or coverage percentage as well as air gap thickness. In general it can be seen that the surface temperature reductions on the exterior building façade wall achieved when a Green Wall was added to the façade were considerable in *warm temperate* climate (C), ranging from 12 to 20.8 °C in the summer period and 5–16 °C in autumn. Even at nighttime, reductions between 2 and 6 °C during the summer and 3 °C in autumn were measured. Regarding the *equatorial climate* (A), the reductions ranged from 1 to 10.94 °C during the day and from 2 to 9 °C during the night. However, in this case there was little data to compare, so it is necessary to conduct more research in these climates.

Regarding the façade orientation influence it is interesting to note that the biggest reductions on the building wall surface temperature occurred mainly in the west orientation, more than in the south or east orientations. Due to the big influence of orientation, this parameter should be investigated in the future.

With regard to the substrate typology, a big disparity of concepts can be observed, such as felt, light substrate, soil, hydroponic medium, mixed substrate, composite peat moss, lightweight growing medium, green roof substrate, inorganic substrate, etc. But in no case a thorough description of the substrate composition was done, that is, its density, thermal properties, etc. The substrate layer provides physical support and nutrients to the plants, and from the thermal point of view the substrate layer is also very important because it acts as thermal insulation. Hence, the composition and thermal properties of the substrate layer are very important and will require further research in this regard since it seems to be an aspect that has been neglected in the research done up to now.

As for the foliage thickness (cm) and plant coverage (%), in the case of Green Walls not enough data was found to draw conclusions, since only three articles provide that data.

Regarding the air layer located between the Green Wall and the building wall façade, just as happens in current ventilated façades, it has a positive impact on the thermal performance of the façade because a microclimate that separates the building façade from the external environment is created within the façade system. In the analysed studies on Green Walls the thickness of the air layer varies from 3 cm to 15 cm (although in one experiment it can achieve up to 60 cm), and this air gap can be opened or closed.

Finally, it can be mentioned that in the case of Green Walls some authors also provided data referring to the heat flux reduction due to the presence of greenery, but the dispersion in the calculation and the results is so large that these data are not comparable. In order to establish comparisons in future research, data about the same parameters should be supplied, such as the reduction on the heat flux through the outer surface of the façade wall of the building, because from this point to the interior of the building, the wall composition varies on each study and data hardly ever can be comparable.

3.3. Simulations

Several authors carried out simulations as a means to study the thermal behaviour of VGS in buildings. In this section a review of these studies, specifying parameters studied, main assumptions of the model, if the model was validated or not, and finally main conclusions, is presented.

McPherson [32] conducted a computer simulation in order to test the effects of irradiance and wind reductions on the energy performance of similar residences located in different U.S. climates. Irradiance reductions from vegetation were modelled using Shadow Pattern Simulation software (SPS), which simulates shade cast from plants on buildings, and MICROPAS, a micro-computer-based energy analysis programme. The studied parameters were solar irradiance and wind reductions and the energy performance of the building. The main assumptions were windows shading coefficient, air change rate, occupancy, and uniform shade from plants. No validation was conducted, and the main conclusions were 21% increment for heating in cold climates (great influence of south and east orientations) and 53% reduction for cooling in warm climates (big influence of the roof and west orientation). For the wind speed, the study concluded that wind reductions were generally beneficial in cold climates, but greenery should not block solar access to south- and east-facing surfaces. In temperate climates, wind reduction lowered annual heating costs by 8%, but increased annual cooling costs by 11%.

In Holm [33] a dynamic model, simulating the thermal effects of vegetation cover on exterior walls using Dynamic Energy Response of buildings system (DEROB), was created. For the simulation, the building mass (high or low), the orientation (equator or west), the season (summer or winter), the climate (hot-arid, hot-humid, Mediterranean) and the exterior temperature were considered. Indoor temperatures were calculated without considering the vegetation properties (assumptions). The model was validated with data from four winter and summer days, and the main conclusions are summarized in Fig. 16. It can be observed that the most pronounced beneficial thermal effect is obtained by leaf cover on the outside walls of low mass in hot-arid climates. On the other hand, the beneficial effect on high-mass buildings in the simulated Mediterranean climate was negligible. In most cases the improvement produced such acceptable indoor climates that no artificial heating or cooling was required.

Di and Wang [12] recorded data, during two summers, on a west-facing wall of a two-story building covered with thick ivy. Conductive heat transfer mechanisms and energy use reduction were also analysed theoretically to determine the basis for the cooling effect of the green façade. The main assumptions were that there was no leaf layers overlap, the leaf temperature was uniform and the ivy had negligible thermal capacity. The main conclusions were reductions of 28% for peak-cooling loads transferred through the wall in summer days and heat gains reduction by solar radiation absorption (40% of the energy absorbed by leaves is lost by convection, 42% by transpiration, and the rest by long-wave radiation to the environment).

Stec [18] developed a simulation model, built with the use of Simulink, in order to define the thermal performance of a double skin façade with plants. A laboratory test facility with lamps was used to validate the simulation process, and the output plant's leaves temperatures were compared with the measured ones. According to the authors, difficulties were encountered with determining the properties of the plant. Thus, transmission was measured in the lab experiment, and absorption and reflection coefficients were assumed from an agricultural literature reference. Results showed that plants create more effective shading system than blinds. Temperature of each layer of the double skin façade was much lower for the case with plants than with blinds. For the same solar radiation, the temperature increase of the plant was about twice lower than for the blinds. Additionally, temperature of the plant never exceeded the temperature of 35 °C, when blinds could exceed 55 °C. Moreover, installation of plants in the double skin façade allowed a reduction of the cooling capacity by almost 20%. A similar result was noticed for the energy consumption of the cooling system.

Alexandri and Jones [34] studied the thermal effect of covering the building envelope with vegetation on the microclimate in the built environment, for various climates and urban canyon geometries. A two-dimensional, prognostic (dynamic) micro-scale model has been developed and programmed in C++, describing heat and mass transfer in a typical urban canyon (Fig. 17). Vegetation geometry (roofs and walls), canyon geometry and orientation, and wind direction were the main studied aspects. Neither the façade system nor the plants species was specified. The first main conclusion was that there is an important potential of lowering urban temperatures when the building envelope is covered with vegetation. Moreover, it can be concluded that the hotter and drier a climate is, the greater the effect of vegetation on urban temperatures. In general when covering with vegetation, the larger the amount of solar radiation a surface receives, the larger its temperature decreases. For all climates examined, green walls have a stronger effect than green roofs inside the canyon. Nonetheless, green roofs have a greater effect at the roof level and, consequently, at the urban scale. In hot climates, energy savings from 32% to 100% for cooling were calculated.

The objective of the research of Wong et al. [22] was to simulate the effects of vertical greenery systems on the temperature and energy consumption of buildings. Thermal analysis simulations (TAS) were performed to determine the effects of vegetation on

Building mass	Orientation	Season	Climate	Outdoor temp. (°C)	Indoor temp. without leaf-cover (°C)	Indoor temp. with leaf-cover (°C)	Effect of leaf-cover
High	Equator	Summer	Hot–arid	21 - 31	19 - 25	19 - 24	Maximum lowered by 1 K
High	Equator	Winter	Hot–arid	7 - 18	15 - 22	15 - 22	Minimum raised by 1 K
High	West	Summer	Hot–arid	21 - 31	19 - 26	19 - 25	Maximum lowered by 1 K
High	West	Winter	Hot–arid	7 - 18	15 - 21	15 - 20	Maximum lowered by 1 K
Low	Equator	Summer	Hot–arid	21 - 31	18 - 33	18 - 28	Maximum lowered by 1 K Indoor cooler than outdoor Acceptable indoor climate
Low	Equator	Winter	Hot–arid	7 - 18	10 - 30	12 - 27	Maximum lowered by 3 K Minimum raised by 2 K Acceptable indoor climate
Low	West	Summer	Hot–arid	21 - 31	17 - 34	18 - 30	Maximum lowered by 4 K Minimum raised by 1 K Indoor cooler than outdoor
High	Equator	Summer	Mediterranean	17 - 26	18 - 24	18 - 24	No significant difference
High	Equator	Winter	Mediterranean	10 - 17	14 - 19	15 - 19	Minimum raised by 1 K
High	West	Summer	Mediterranean	17 - 26	18 - 27	18 - 25	Maximum lowered by 2 K Acceptable indoor climate
High	West	Winter	Mediterranean	10 - 17	10 - 17	15 - 19	Maximum raised by 2 K Minimum raised by 5 K Acceptable indoor climate
High	Equator	Summer	Hot–humid	22 - 32	19 - 26	19 - 24	Maximum lowered by 2 K Acceptable indoor climate
High	Equator	Winter	Hot–humid	12 - 25	17 -22	17 - 22	No difference Acceptable indoor climate
High	West	Summer	Hot–humid	22 - 32	19 - 26	19 - 25	Maximum lowered by 2 K Acceptable indoor climate
High	West	Winter	Hot–humid	12 - 25	17 - 22	17 - 21	Maximum lowered by 1 K Acceptable indoor climate

Fig. 16. The effect on indoor temperature by leaf-covered exterior walls [33].

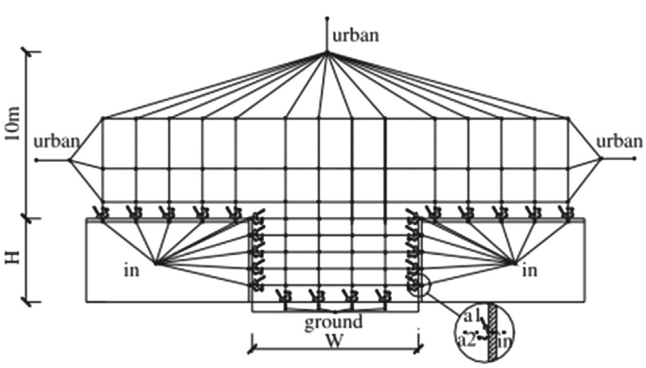


Fig. 17. Two-dimensional canyon model [34].

thermal comfort and energy consumption (Fig. 18). Furthermore, a thermal calculation of the envelope thermal transfer value to obtain their effects on the thermal performance of the building envelope was done. For the calculation some data from previous research about green roofs were used (turf, substrate, LAI, plant species, etc.), assuming the same conditions for green walls. As mentioned in Section 3.2. *Green walls*, for these simulations different plant coverages to a hypothetical building were given. One of the main conclusions was that the shadow effect is closely related to the density of the foliage, which was related to the LAI of the fern species used (Boston Fern (*Nephrolepis exaltata*)). In the conclusions, it was found that the key behind shading is thicker greenery. Moreover, reductions between 10% and 31% energy cooling load were calculated due to the effect of greenery.

Kontoleon and Eumorfopoulou [7] studied the effect of the orientation and proportion (covering percentage) of a plant-covered wall layer on the thermal performance of a building. In this paper the main objective was the study of the influence of a 5 cm insulation layer in the façade wall of a theoretical building of $10 \times 10 \times 3\ m^3$ (Fig. 19). Furthermore, a 25 cm vegetation layer, with an estimated thermal conductance value of $2\ W/m^2$, was added to the calculations in order to simulate its effect on the thermal behaviour of the building. Surface and indoor temperatures as well as energy requirements for a set-point of 20 °C were the main parameters calculated. Results showed that vegetation had a crucial influence by the absorption of huge amounts of solar energy. The exterior/interior surface reductions calculated were 1.73/0.65 °C for the north façade, 10.53/2.04 °C for the east façade, 6.46/1.06 °C for the south façade and 16.85/3.27 °C for the west façade. This effect implied cooling load reductions of 4.65% for the north, 18.17% for the east, 7.60% for the south and 20.08% for the west.

Jim and He [29] developed a thermodynamics transmission model to simulate heat flux and temperature variations of vertical greenery ecosystems. The studied parameters were global solar radiation, diffuse solar radiation and seasonal heat flux. In order to validate the simulation a little experiment, composed by four green wall units ($50 \times 85 \times 35\ cm^3$) oriented, two to the north and two more to the south, was carried out. The modules were placed 15 cm in front of the railing of the roof, and this 15 cm air gap was open. As mentioned in Section 3.2. *Green walls*, the results showed that when global solar radiation and temperature of the south control wall had reached maximum values, the south green walls had recorded reductions up to 8.83 °C.

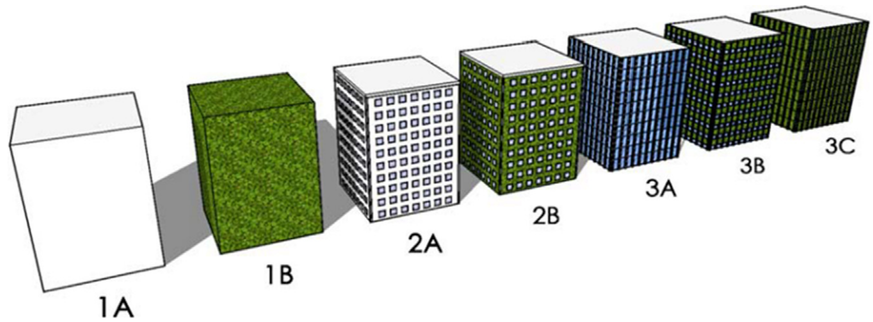


Fig. 18. Scenario 1 (left), 2 (centre) and 3 (right) of TAS simulations [22].

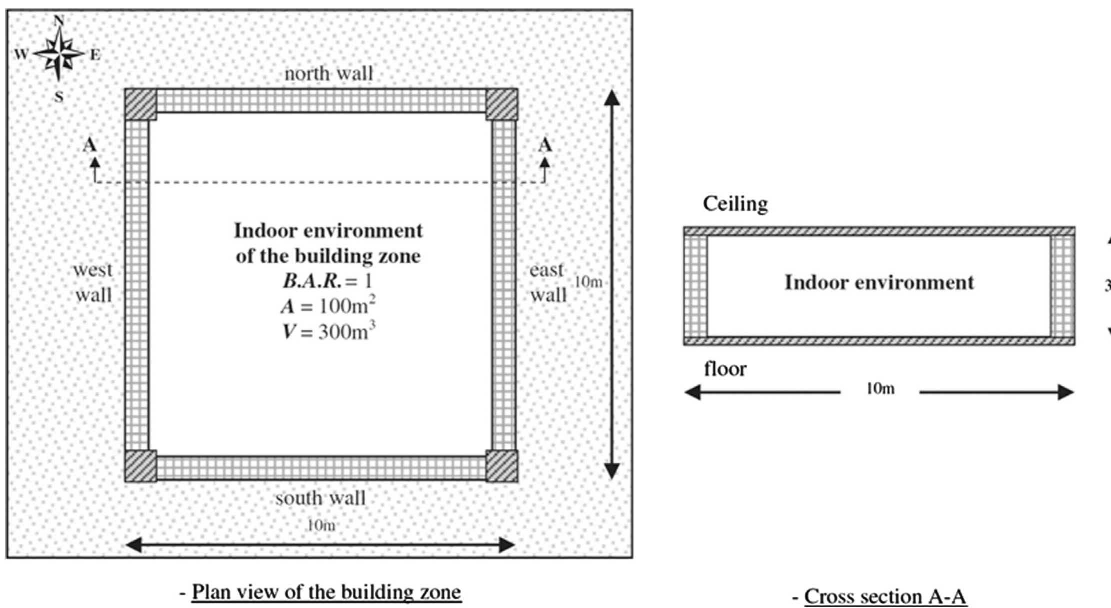


Fig. 19. Schematic representation of the analysed building zone [7].

Susurova et al. [17] developed a mathematic model to simulate the thermal performance of vegetated exterior façades. Data collection for validation took place over 3 days in a south traditional green façade (*Parthenicissus tricuspidata*) at the Illinois Institute of Technology in Chicago. The main goal of this study was to consider the variable plant characteristics in the simulations, because according to the authors, previous studies only considered aspects such as the façade properties, building orientations or weather conditions. However, due to the lack of data related to the vegetation and the difficulty to obtain it, several assumptions were carried out (leaf absorptivity coefficient, radiation attenuation coefficient, typical stomacal conductance, etc.). As explained previously in Section 3.1.1 Traditional Green Façades, the main conclusions from the simulation process were that solar radiation, façade orientation, and air temperature were more influential over the green façade thermal behaviour than the air relative humidity, wind speed or the plant parameters. On sunny days, a plant layer on a brick façade was estimated to reduce its exterior surface temperature by 0.7–13.1 °C, to reduce the heat flux through the exterior wall by 2–33 W/m^2, and provide an effective *R*-value of 0.0–0.71 m^2 K/W, depending primarily on the wall orientation, the leaf area index, and the radiation attenuation coefficient.

In Table 9 the reviewed literature on simulations about VGS is organized and the main features and conclusions are summarized. Because simulations allow working with a wide range of different climates, so as not to complicate the summary table, in this case studies have not been classified by climatic zones. Only the differentiation among Green Walls and Green Façades, and their typologies, has been considered.

From the nine simulation studies analysed, three did not specify what typology of façade was considered, four referred to Green Façades, three to Traditional Green Façades and one more was a Green Double-skin Façade, and finally two studies concerning Green Walls were found.

Regarding the plant species, no plant species were specified in the three simulations in which the constructive system was not specified. With respect to the four simulations about Green Façades, two of them used ivy, an evergreen plant, and two more used Boston ivy, a deciduous plant, although being deciduous or evergreen did not affect the main conclusions because the cooling period was considered mainly in these four studies (summer).

Regarding the two Green Walls simulations, similar to the studies of real or experimental Green Walls, species are very varied, but mainly shrubs and herbaceous plants well adapted to the local climatic conditions.

With reference to the mathematical models and software used, great variability and little continuity between consecutive studies can be observed. The most analysed parameters were surface temperature and environment temperatures, the heat flow through the wall, and the energy savings achieved. In general a great difficulty to characterize the vegetation in an objective way can be seen, which results in a large number of assumptions used by the authors in order to conduct their simulations. This fact highlights the importance of carrying out further research on the plant properties in different climates. Indeed the large list of assumptions also questions the necessity of actually knowing in detail all the physiological properties of plants (absorption of radiation, transpiration, stomatal opening, etc.). With regard to the models' validation, except one study which employed data from two consecutive summers, it can be observed that usually the periods of the data collection were too short, between 4 and 12 days; even in some of the found studies the models used were not validated with real data.

Regarding the main conclusions from the simulation studies on VGS, it can be generally stated that VGS are an effective tool for energy savings during the cooling period in *warm temperate* (C) and *arid* (B) climates, with reductions between 5% and 50%, the most frequent being between 20% and 30%, taking special consideration of the West façade orientation influence. Only one of these simulation studies provided a conclusion regarding the increase in energy consumption for heating (21%), being one of the reviewed studies in which neither the green system nor the plant species was specified. These lonely negative data about these systems during the heating period suggests that further studies should be carried out during the rest of the year (winter, spring and autumn) and that it will be necessary to evaluate their thermal behaviour for all year.

Comparing the different VGS systems, in view of the data in Table 9, it seems that Green Façades are the most efficient in reducing power consumption during cooling periods but the fact that there are only a few simulations on Green Walls does not allow actually confirming this statement.

4. Related literature

The articles referenced in this review refer directly to the use of VGS for energy savings in buildings. Nevertheless, there is a group of related topics articles that, although do not deal directly with green walls or façades, are interesting for this work. These papers have been grouped by topics, and a summary of the outstanding aspects is presented.

4.1. Influence over urban environment

The urban heat island effect is caused by a variety of factors, such as anthropogenic (combustion heat, people, etc.), less evaporative cooling due to the lack of vegetation, less cold wind in the streets, the configuration of streets, solar heat stored in the urban fabric, etc. Cities have large areas of asphalt and other dark materials that have low albedo (reflectivity) resulting in the absorption of radiant heat from the sun and re-radiation at night.

Since vegetation not only has higher albedo than most of the common building materials used but also provides cooling through evapotranspiration, VGS contribute to the reduction of the heat island effect. In addition, by increasing urban green areas airflows are created so that the hot air generated above hard surfaces rises quickly and it is replaced by fresh air from green areas. Those airflows contribute to the heat island effect reduction as well.

Some authors have studied the global effect of greenery in buildings on the whole urban environment.

Wilners [35] highlighted the importance of green areas on the improvement of the urban climate. The author pointed out the Leaf Area Index (LAI), the evapotranspiration and wind as the most important factors.

Ochoa [36] collected data in an urban environment in order to characterize the effect of vegetation in outdoors comfort conditions (temperature, humidity, noise, etc.). Several cases were analysed (squares, pergolas, streets, etc.) and the author came to the conclusion that the shadow effect is perhaps the most important since it directly influences surface temperatures.

Bass and Baskaran [37] conducted different experiments to evaluate roof and vertical gardens as an adaptation strategy for urban areas. Results show the shadow effect provided by vegetation. Furthermore, Bass [38] conducted a simulation in which the effect of an evergreen shrub hedge (*Juniperus* sp.) located near the buildings was studied. The main conclusion was that the possible increment of the energy consumption in winter due to the shading effect was compensated due to the climate modification, in the air gap between the building wall and the green hedge, as well as the wind speed reduction.

Ong [21] proposed a "green plot ratio" index, based on LAI, as a tool to make the urban planning more sustainable.

According to Domurath and Schroeder [39] the full efficiency of vertical vegetation can only be achieved by high leaf area indices (LAI) per façade unit. This means better plant growth control using pre-grown modules with easy replacement, the use of hydroponics techniques to control automated supply of water and nutrients, the use of new stronger and lighter materials in the modules design, and finally trying to automate any subsequent maintenance activity.

Francis and Lorimer [40], discussing the potential of living roofs and walls, stated that the main problems of implementation are associated with costs of investment and maintenance, as well as the social perception of these systems (society does not value enough the ecological profit and biodiversity).

Elinç et al. [41] suggested the possibility of using green walls as a means to improve not only the aesthetics but also the inner city ecosystem in order to attract more tourism to a specific region under the Mediterranean climate.

4.2. Shade from trees

Although this article deals basically with articles relating to VGS, there are some very interesting papers related to the shade produced by trees on buildings and the consequences of this fact on the thermal performance of the building. This landscaping approach essentially involves the study of the shade effect and the barrier effect of the wind on buildings from the surrounding trees.

Akbari et al. [42] conducted a simulation based on real data in order to study the peak power and cooling energy savings of shade trees under Mediterranean climate. The most remarkable results were the significant building wall surface temperature reductions (shade effect), between 11 and 15 °C, the wind speed reductions, about 13–16%, and the energy savings achieved, between 26% and 47%, with peak cooling reductions of 0.6–0.8 kW during the monitoring period. The authors stated how difficult it is to simulate the effect of shade trees and consequently different simulation proposals are presented.

Papadakis et al. [43], in an experimental investigation, concluded that plants constitute an excellent passive system for solar control of buildings offering significant advantages over conventional artificial sunscreens. The peak solar radiation in the non-shaded area reached almost 600 W/m^2 whereas at the same time the corresponding value for the shaded area was under 100 W/m^2. Besides, as evaporated water from trees caused an increase of absolute humidity of about 1–2 kg water per m^3 dry air and, at the same time, trees block the air movement (barrier effect), the refresh rate of the air between the wall and the trees was lower than in the un-shaded area.

4.3. Influence over indoor environments

The effect of vertical greenery systems over indoor environments is another topic studied. In this regard, Fernández-Cañero et al. [44] studied one way of improving the substrate properties of a green wall in order to assess its cooling potential in indoor applications. Indoor temperature reductions of up to 6 °C were achieved as well as increments about 15% for the indoor relative humidity.

Franco et al. [45] used a low-speed wind tunnel to study the behaviour of different synthetic substrates used in active green walls for indoor environments. According to the authors, the cooling efficiency was enhanced with vegetation and low air speed. Moreover, specific consumption of water is higher with vegetation at higher air speeds. Therefore, low air and water flows were recommended to ensure a homogeneous wetting of the substrate surface.

4.4. Miscellaneous

Some researchers studied the environmental impact assessment of vertical greenery systems. In these studies on Life Cycle Assessments (LCA) the amount of energy consumed during the use phase of building systems is often a decisive factor. According to the authors, more research in this direction is necessary because it is not clear whether these systems are sustainable, due to the materials used, maintenance, nutrients and water needed [46,47]. Referring to the issue of maintenance, and considering the classification of VGS discussed in Section 2.1, it is clear that significant differences exist between construction classification systems. Therefore, further in-depth studies must be conducted on the plant species used, on the costs of investment and maintenance, on the associated damage, on the complexity of the used technology, as well as on the interaction of these systems with the architecture (from the point of view of the architectural composition of the building). In this regard, it seems that vegetated facades, specifically Double-skin Green Façades, offer better prospects in terms of providing vertical vegetated surfaces integrated into the building, by simple constructive solutions, easy to remove if it is necessary, with extensive maintenance.

Finally, there are various interesting papers related to vertical greenery systems but not directly linked to energy savings. Regarding the sound insulation effects of vegetation when it is incorporated in buildings, previous studies usually consider the contribution of green roofs to acoustic insulation, while references to vertical green systems are scarce [48,49,50,51,52]. Relating to the insulation properties of green systems, it is known that vegetation can reduce sound levels in three ways. First, the sound can be reflected and scattered (diffracted) by plant elements, such as trunks, branches, twigs and leaves. As a second mechanism there is the absorption by vegetation. This effect can be attributed to mechanical vibrations of plant elements caused by sound waves, leading to dissipation by converting sound energy to heat. As a third mechanism, it could be also mentioned that sound levels can be reduced by the destructive interference of sound waves by the soil layers' presence. From these few studies that consider the acoustic insulation capacity of VGS, it can be deduced that these systems positively contribute to improving the building/city acoustics. However, these experiments are very different, and the results are so diverse that it is difficult to state the real contribution of green walls.

Other studies face the potential of VGS to attract particles of pollution [53], or their value as habitats for wildlife, for example urban birds [54].

Although the system designs and patents have not been a specific task of this review, there are some papers discussing about improving the design of vertical green systems [55,56].

5. Conclusions

This review organizes and summarizes the literature on Vertical Greenery Systems (VGS) as a passive tool for energy savings in buildings.

From this literature review, it can be concluded that when studying the contribution of VGS to the passive energy savings in buildings, four key aspects that may influence its operation must be considered:

- ***Systems classification***: In order to compare research results, the kind of system used should be clear.
  - Classification of Vertical Greenery Systems for buildings clearly summarizes the main typologies of VGS (Table 1).
  - When organizing the reviewed literature by constructive systems, according to the classification from Table 1, it can be seen that there are few studies conducted around the world. Specifically, 7 studies for Traditional Green Façades (Tables 2 and 3), 10 studies for Double-skin Green Façades (Tables 4 and 5), 8 studies for Green Walls (Tables 6 and 7), and 9 studies for simulation studies on VGS (Tables 8 and 9).
- ***Climate influence***: Climatic conditions influence VGS operation because climate affects directly the thermal performance of the building, and the specific aspects of plants such as the species to be used, their growth rate, their transpiration, etc.
  - Most of the studies found were located in the quadrant corresponding to the intersection of North and East hemispheres (Fig. 6a and b), specifically in Europe (mainly Green Façades) and Asia (mainly Green Walls).
  - A lack of studies in areas of the world that receive more radiation is observed. It is important to point out here that further researches should be carried out in these areas because these systems could be more effective (Fig. 7).
  - It can be desirable to use the Köppen classification to unify criteria in order to compare properly the research results relating to VGS.
  - Most studies were located in warm temperate (C) climate, followed by equatorial (A) and snow (D) climates, respectively. In general there was a significant lack of studies in all climates, but especially in arid climate (B). Tables 2, 4, 6 and 8 show the climatic classification for the reviewed literature.
- ***Plants species influence***: Different typologies of VGS use different plants species, and this fact must be taken into account when studying their thermal behaviour.
  - For Green Façades climbing plants are usually used, which can be evergreen or deciduous, fact that can affect significantly their performance throughout the year, from the thermal point of view. From this literature review it can be stated that the number of species actually used is very limited and we are not taking advantage of the large number of species available in different climatic zones (Tables 3 and 5).
  - In Green Walls, herbaceous and shrubs species (occasionally climbing plants) are the most common, usually well adapted to local climatic conditions, and always evergreen. The number of species used in the analysed studies on Green Walls was high. However, this implies different thermal behaviours in the same Green Wall. Further studies about the properties of each plant species in each climate will be needed (Table 7).
  - In the simulation studies, the listed plant species are those used for the model validation. Generally, the properties of the plants were assumed due to lack of data (thermal conductivity, shading coefficient, etc.).
- ***Operational methods***: Regarding to the potential for passive energy savings of VGS, four main effects should be considered, the Shade effect, the Cooling effect, the Insulation effect, and the Wind barrier effect (Tables 10 and 11). Generally, most studies consider only the shadow effect, and the need to conduct more studies about the others effects is evident.
  - *The Shade effect* consists basically on the solar radiation interception provided by plants.

- *The Cooling effect* takes place due to the evapotranspiration from the plants and substrates.
- *The Insulation effect* is related to the insulation capacity of the different layers, such as the air in the plant layer, possible intermediate air layers, the substrate layers, etc.
- *The Wind barrier effect* refers basically to the capacity of the vertical green system, plants and support structure, to modify not only the direct wind effect over the building façade.

In Tables 3, 5, 7 and 9 the literature regarding Vertical Greenery Systems is organized and summarized and its main conclusions and characteristics are shown, making it easier to compare similar studies. In the case of Traditional Green Façades (Table 3), Double-skin Green Façades (Table 5) and Green Walls (Table 6) studies were ordered considering the climatic classification so that comparisons of results can be easier. In the case of simulation studies (Table 9), since simulations allow working with a wide range of different climates, so as not to complicate the summary table, in this case studies have not been ordered by climatic zones.

In addition to the information from the summary tables, in general for each VGS typology the following conclusions can be highlighted:

For Traditional Green Façades (Table 3):

- The most interesting parameters to consider in their analysis and consequently in the subsequent design are the period of study (cooling, heating, all year), the species used, the façade orientation, and the foliage thickness.
- Most of the studies reviewed correspond to existing façades, limiting the study period to the summer, and using two predominant species, a perennial specie, ivy (*Hereda helix*), and a deciduous specie, Boston ivy (*Parthenocissus tricuspidata*). Therefore, in future research the number of experiments in different climates and the number of plant species used must be increased and, moreover, in these new studies the rest of the year must be considered as well (winter, spring and autumn).
- In the summer period, the measured reductions in the exterior surface temperature of the building wall ranged from 1.7 °C to 13 °C on *warm temperate* climate (C) and between 7.9 and 16 °C in *snow* climate (D).
- East and West orientations can have a great importance in energy reductions during summer. Further studies are needed regarding the impact of the orientation of the façades.
- A direct relation between foliage thickness and the surface temperature reduction, so that the thicker the foliage, the higher the reduction.

For Double-skin Green Façades (Table 5):

- The most interesting parameters to consider in their analysis and consequently in the subsequent design are the period of study, the species used, the façade orientation, the foliage thickness (or the coverage percentage), and the air gap thickness between the plant layer and the building façade wall.
- Seven of the ten analysed studies were experiments and the rest refer to existing façades. This fact indicates that this typology is of great interest to the scientific community.
- Most studies are located in *warm temperate* climate (C) with one exception located in *equatorial* climate (A). In addition, mostly the summer period was considered, the south being the most common façade orientation. Therefore, it is necessary to carry out more studies in different climates, throughout the whole year and in different façade orientations.
- Generally, the reduction on the exterior surface temperature of the building façade wall ranged from 1 °C to 15.18 °C for the studies located in *warm temperate* climate (C).
- Because data available are too sparse, no conclusion referring to the influence of foliage thickness or coverage percentage can be drawn.
- Other interesting issues that appear in the reviewed studies, which must be studied in depth, are the effect of evapotranspiration from plants, the effect like ventilated façade of the intermediate layer of air, and the characterization of the effect of shadow by Leaf Area Index (LAI), usually used in the characterization of agricultural crops.

For the Green Walls (Table 7):

- The most interesting parameters to consider in their analysis and consequently in the subsequent design are the period of study, the species used, the façade orientation, the foliage thickness (or the coverage percentage), the substrate typology and thickness, and the air gap thickness between the plant layer and the building façade wall.
- Of the eight studies analysed five were experiments, two of them were simulation studies and only one was the analysis of a real case.
- The studies on Green Walls were mainly located in *warm temperate* climate (C), although two more were located in *equatorial* climate (A). These studies were carried out mostly during the summer and autumn periods. In the case of Green Walls plant species are usually herbaceous and shrub well adapted to local conditions. Therefore, studies throughout the year and in different climatic locations will be necessary.
- Reductions in external surface temperatures of the building façade wall were considerable in *warm temperate* climate (C), ranging from 12 to 20.8 °C in the summer period and 5–16 °C in autumn.
- The largest reductions in external surface temperature took place in South–West and East façade orientations.
- With regard to substrate typology, a huge disparity of concepts can be observed, such as felt, light substrate, soil, hydroponic medium, mixed substrate, composite peat moss, lightweight growing medium, green roof substrate, inorganic substrate, etc. But in no case a thorough description of the substrate composition was carried out, that is, its density, thermal properties, etc. Therefore it will be necessary to study this issue in depth in future studies.
- For the foliage thickness (cm) and plant coverage (%), in the case of Green Walls not enough data was found to draw conclusions.
- Regarding the air layer located between the Green Wall and the building wall façade, just as happens in current ventilated façades, it has a positive impact on the thermal performance of the façade because a microclimate that separates the building façade from the external environment is created within the façade system. In the analysed studies on Green Walls the thickness of the air layer varies from 3 cm to 15 cm (although in one experiment it reached up to 60 cm), and this air gap can be opened or closed.

For simulations studies on VGS (Table 9):

- From the nine simulation studies analysed, three did not specify the typology of the façade considered, four referred to Green Façades, three to Traditional Green Façades and one more was a Green Double-skin Façade, and finally two studies concerning Green Walls were found.
- In reference to the mathematical models and software used, huge variability and little continuity between consecutive studies were observed.
- In general, one difficulty in characterizing the vegetation in an objective way can be seen, which results in a large number of assumptions used by the authors in order to conduct their simulations.
- With regard to the models' validation, except one study that employed data from two consecutive summers, it can be observed that usually the periods of data collection were too short, between 4 and 12 days, and in some of the studies the models used were not even validated with real data.

– From the simulation studies on VGS, it can be generally stated that the VGS are an effective tool for energy savings during the cooling period in *warm temperate* (C) and *arid* (B) climates, with reductions between 5% and 50%, the most frequent being between 20% and 30%, especially considering the West façade orientation influence.
– Only one of these simulation studies provided a conclusion regarding the increase in energy consumption for heating (21%). This lonely negative data about these systems during the heating period suggests that further studies should be carried out during the rest of the year (winter, spring and autumn) and that it will be necessary to evaluate their thermal behaviour for the whole year.

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