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The impact of greenery systems on building energy: Systematic review

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ABSTRACT

During the last decade, greenery systems attract building designers for several public services such as the potential of energy savings in buildings. This literature review presents a systematic analysis of the impact of greenery systems on building energy use. The greenery systems are exterior to the building enclosure, resulting in a reduction of external surface temperature and heat transfer, particularly in certain climates. The review analyzed 56 articles from 2010 to early 2019. The revision criteria were based on eight measured indoors and outdoors parameters, the number of residents, and the amount of heat reduction or energy saving. It is found that not all the articles have measured all the environmental parameters, and few have conducted their research in an occupied place. However, the impact of solar radiation on building envelopes varies dramatically according to the seasonal and spatial variation, leaf area index of plants, and moisture retains in the plants. In addition, there are significant differences in laboratory and field studies of greenery systems, where less impact of greenery systems on energy use. In conclusion, greenery systems have a positive impact on saving energy, but they cannot replace air conditioning systems to maintain thermal comfort of residents, and other alternatives can provide promising solutions. More research should be conducted in real buildings with residents in different activities to have a comprehensive assessment of the impact of greenery systems.

1. Introduction

The urban population has been rapidly increasing, reaching 68% by 2050 [1]. This increase leads to significant environmental issues including lack of green areas, urban heat island effect, greenhouse gas emissions, increase in energy consumptions, increase surrounding ambient temperature [2,3]. These negative impacts are indirectly correlated to discomfort in the indoor environment. For that reason, people tend to spend around 90% of their time indoors [4,5]. This long-period indoors is often associated with building energy use. Building occupants have a profound impact on energy consumption. This impact is governed by occupant comfort based on building operational parameters, such as the indoor air temperature, relative humidity, lighting levels, and required ventilation. Maintaining comfortable conditions requires a substantial amount of energy from the use of heating, ventilation, and air conditioning (HVAC) systems [6].

Using sustainable energy resources is a suitable solution to mitigate the energy consumption of buildings. Some renewable energy systems are geothermal systems [7], solar systems [8], wind turbines [9] to provide electric power to operate building facilities such as air conditioning systems, lighting, and appliances. In addition, novel building designs are constructed to mitigate the building thermal load, such as constructing Trumbe and solar walls [10,11] and day-lighting systems [12]. Moreover, new air conditioning systems are implemented like radiant heating and cooling panels on the walls and floor to reduce energy consumption and enhance thermal comforts [13,14].

Since solar radiation is the most contributor to building the thermal load, it is recommended to reduce it by isolating building envelope. Plants have been used as green systems as a sustainable solution for the building envelope, such as vertical vegetation systems and green roofs. Greenery systems have numerous benefits for urban areas and the environment. They absorb the incident solar radiation, reduce the air temperature of the surroundings, mitigate the urban heat island, and increase the aesthetic value of the building [15,16]. Also, the greenery systems reduce the surface temperature of walls and roofs, which leads to reduce the building thermal load resulting in reducing the power consumption of buildings [17,18].

Researchers have been interested in greenery systems for decades. There are 15 review articles to discuss the benefits of the greenery systems in the range of 2010–2018 [2,18–31]. The greenery system depends on the location of plants and growing media [20,28] and can be classified into green façades, living walls, and green roofs. When the growing media is the ground, the system is called green façades, which have two types: direct façades including traditional façades, and

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indirect façades, including continuous guides, modular trellis, or double skin façades. When the growing media is embedded in the building walls, the system is called living walls or green walls, which also have two main types: continuous green walls by using continuous screen or geotextile felt, and modular green walls by using trays, vessels, or planters. Lastly, when the growing media is on the roof of a building, this system is called green roofs. Less commonly investigated are green balconies, indoor sky gardens [18], and adjoining vegetation [30]. In addition, vegetation system design [21] and system requirements [28] are considered. These systems requirements include supporting elements, substrate, drainage, irrigation, and planting. Also, few review articles have analyzed the research methodology conducted to the studies of greenery systems and categorized into experimental studies, observational studies, and numerical studies [20,30]. The thermal performance of greenery systems has been studied in seven review articles [18–21,28,30,32]. Thermal performance can be defined as the temperature difference between building envelope layers, and sometimes relative humidity. The comparison between building envelopes with and without vegetation is necessary to measure the difference in heat flux through the building envelopes under the same environmental conditions. The vegetation system has several benefits, such as the insulation effect, the cooling effect on the building envelope, reducing urban heat island, solar absorption, and wind barrier [18,33,34].

Although a large number of review articles in the last decade, all the review articles did not provide a precise analysis of indoor environment with residents inside the buildings and did not discuss the impact of the greenery systems on actual, occupied buildings to help the decision making of constructing such systems. Therefore, this review paper is written to fill this gap. The purpose of this review paper is to systematically review the impact of greenery systems, including green roofs, green façades, and green walls, by considering the following:

a. A systematic analysis of the thermal effect of applying greenery systems on buildings. This includes the environmental conditions of outdoors and indoors and microclimate conditions of the vegetated object.
b. The amount of heat flow reduction through building envelopes by applying the greenery systems,
c. The amount of energy saving of any mechanical device that is used to provide a suitable thermal comfort such as air conditioning systems, ventilation systems, and heating systems in actual buildings or experiments
d. The impact of greenery systems on occupants in field studies.

The review paper is divided into four main sections: research methodology to capture most related articles for the analysis, the results of the systematic analysis of the articles, and the discussion upon the analysis followed by the conclusion.

2. Research method

This review paper follows a systematic review adopting Moher's 2010 protocol [35] to focus on greenery systems. This protocol comprises four phases for conducting the review analysis, including identification, screening, classification, and inclusion, as illustrated in Fig. 1.

2.1. Identification

This phase is to identify the articles related to the greenery system. The central databases used in research are Web of Science (https://apps.webofknowledge.com) and Google Scholar (https://scholar.google.ca) since they are the most popular and accessible database at the University of Toronto. The searching keywords are combined keywords of plants/vegetation and energy, which are combined with Boolean operators such as AND OR. The keywords for plants are: “plants”, “green plants”, “potted plants”, “ornamented plants”, “indoor gardening”, “vegetation”, “greenery”, “vertical greenery systems”, “green façades”, “living walls”, “green walls”, or “green roofs”. Same searching trend was used for energy saving: “energy saving”, “energy consumption”, “power consumption”, “heat flux”, “energy reduction”, or “heat reduction”. The searching process was also specified publication year range from 2010 to early 2019.

2.2. Screening

The screening process considers scanning the collected articles to exclude the duplicated articles from Google Scholar and Web of Science database, and non-English articles, non-peer-reviewed articles, conference papers, and opinion articles, and articles are not related to the greenery systems and the eligibility criteria for this review.

2.3. Classification

In this phase, many disciplines have been conducted with greenery systems. These disciplines can be classified as (a) thermal performance including the analysis of surrounding temperature and heat transfer, and energy savings, (b) vegetation including the selection of plants species, the physics of plant physiological processes such as transpiration, evapotranspiration, growth, and leaf index, (c) air quality including the air and water pollutant removal indoors and outdoors, (d) psychological rehabilitation including psychological effects of the greenery systems on elderly and children for health improvement, (f) economic analysis including the life cycle assessment of the greenery systems, and lastly (g) acoustics and aesthetic values.

2.4. Inclusion

This review paper focuses on the experimental design and methodology for three greenery systems: green façade, green or living wall, green roof. The types of conducted studies are classified into experimental measurements, simulation analysis, mathematical modeling, and field measurements. The space design can be cubes, buildings, homes, and walls. The four phases are explained with numbers of exclusion and inclusion for each process in Fig. 1. The results for this searching process was 71 articles, including 15 review article [2,18–31] and 56 research articles in 2010 to early 2019.

The research method is to capture all the related scientific articles of greenery systems from 2010 to early 2019 (from January to March) in order to analyze the effect of greenery systems on indoor conditions. The research articles are organized in reverse chronological order, as shown in Tables (1 and 2). Fig. 2 presents the review scheme for a research article from 2010 to early 2019. The right-handed picture shows an occupied house with no greenery system equipped with an air conditioner for heating and cooling to achieve the thermal comfort, while the left-handed picture shows an occupied and equipped house with three types of greenery systems. A study may focus on one or two greenery systems, may be conducted on a building, a cube, and a wall, and the place may be occupied and unoccupied. To follow this review scheme, the captured studies have been organized and analyzed based on the following:

1. General information mentioned in the studies: such as types of greenery systems, location and environment, type of study, and season, excluding the plant species.
2. Providing a comparison to bare building envelopes.
3. The microclimate parameters can be divided into outside and inside parameters. The outside parameters are ambient temperature (T_o), ambient relative humidity (RH_o), external wall surface temperature (T_{se}), the solar radiation (SR), and the wind speed (WR. The inside parameters are the inside wall surface temperature (T_{si}), the indoor air temperature (T_i), and the indoor air relative humidity (RH_i).
4. External and internal surface temperature reduction, and

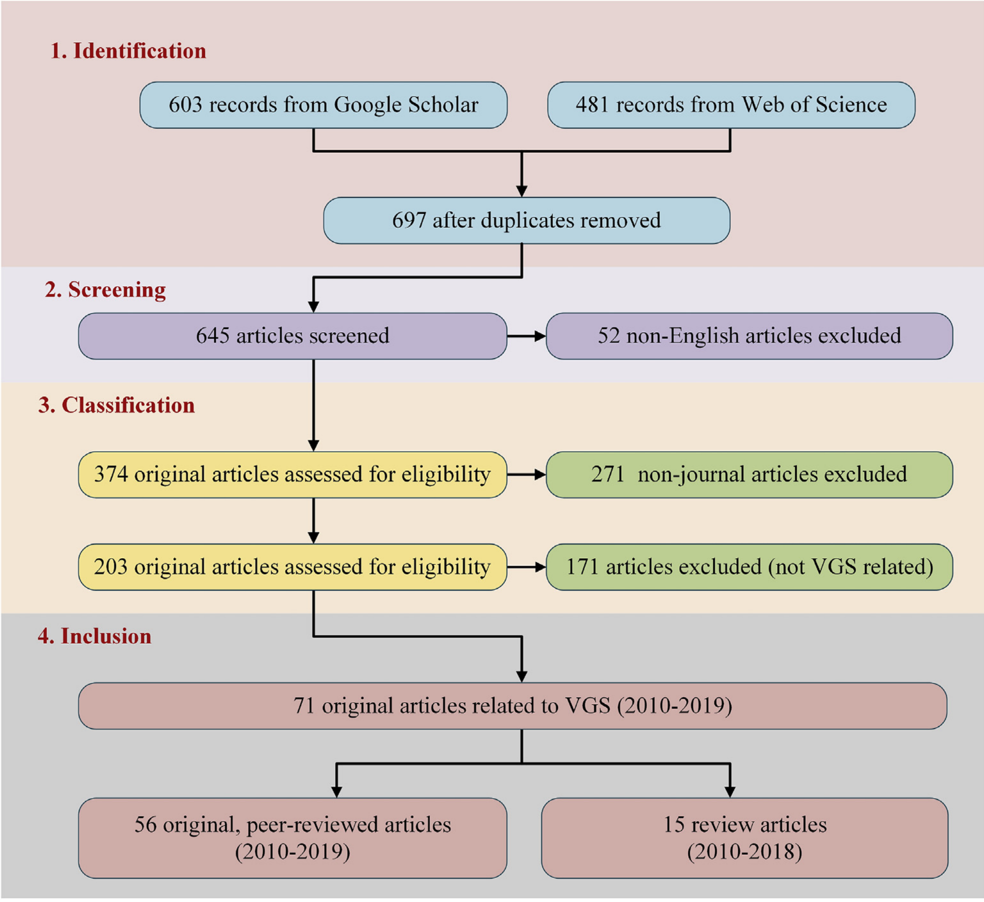

Fig. 1. The process of article selection in the review.

5. Amount of heat reduction (HR) and energy savings (ES) in percentage.

The external surface temperature reduction (TR_{ex}) is the difference between external surface temperatures of bare surfaces and vegetated surfaces behind the plants and the growing media as in Equation 1. The internal surface temperature reduction (TR_{in}) is the difference between internal surface temperatures of bare surfaces and vegetated surfaces as in Equation 2.

$$TR_{ex} = T_{se,w/o} - T_{se,w/p} \tag{1}$$

$$TR_{in} = T_{si,w/o} - T_{si,w/p} \tag{2}$$

The heat transfer reduction (HR) represents the reduction value of the total heat transfer through the building enclosure (walls and roofs), as expressed in equation 3. The energy saving (ES) represents the reduction or saving in the energy consumption of the entire building or the HVAC system used in the model building, as described in equation 4.

$$HR = \frac{Q_{w/o} - Q_{w/p}}{Q_{w/o}} \times 100 \tag{3}$$

$$ES = \frac{E_{w/o} - E_{w/p}}{E_{w/o}} \times 100 \tag{4}$$

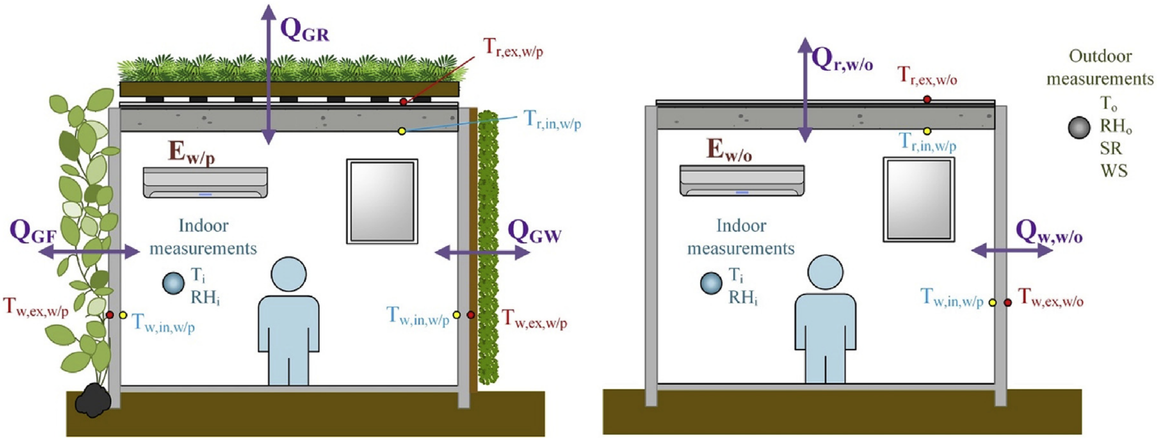

Fig. 2. A representative scheme of reviewing articles related to the greenery systems.

Table 1
Organization of previous research articles from 2010 to early 2019 (56 articles).

References	Types of greenery systems	Location	Space	Types of study	Season	W/O plant	Parameters			
							Outside (T_o - RH_o – SR – WS - T_{se})	Inside (T_{si} - T_i - RH_i)	Energy	Others
Xing et al. (2019) [75]	GF	China	Model	E	Winter	Yes	(√ - √ - √ - √ - √)	(√ - √ - √)	HR,ES	–
Pan et al. (2018) [49]	GW	China	Model	E	Year	Yes	(√ - √ - √ - √ - √)	(√ - √ - 0)	HR	–
Vox et al. (2018) [63]	GF	Italy	Cube	E	Year	Yes	(√ - √ - √ - √ - √)	(0 - 0 - 0)	HR	–
Widiastuti et al. (2018) [72]	GF	Indonesia	Cube	E	Monsoon	Yes	(√ - √ - 0 - √ - √)	(√ - √ - √)	HR	–
Yuan and Rim (2018) [47]	GW, GR	USA	Model: Office, hospital, school	S	Year	No	(√ - √ - √ - 0 - 0)	(0 - √ - 0)	ES	–
Bianco et al. (2017) [50]	GW	Italy	Cube	E	Year	Yes	(√ - 0 - √ - √ - √)	(0 - √ - 0)	HR	
Coma et al. (2017) [67]	GW, GF	Spain	Cube	E	Year	Yes	(√ - 0 - √ - 0 - √)	(√ - √ - 0)	ES	–
Cuce (2017) [86]	GF	UK	Building: University campus	F	Spring	Yes	(√ - √ - √ - √ - √)	(√ - √ - 0)	HR	–
Dahanayake et al. (2017) [83]	GW	China	Building	S	Summer	Yes	(√ - √ - 0 - 0 - √)	(0 - √ - 0)	ES	–
Dahanayake and Chow (2017) [64]	GW	China	Building	S & M	Year	Yes	(√ - √ - √ - 0 - √)	(√ - √ - 0)	ES	–
Foustalieraki et al. (2017) [66]	GR	Greece	Building: supermarket	F & S	Year	Yes	(√ - √ - 0 - √ - √)	(0 - √ - 0)	ES	–
Haggag et al. (2017) [37]	GF	United Arab Emirates	House	F	Summer	Yes	(√ - 0 - √ - √ - √)	(√ - √ - 0)	HR,ES	Financial analysis
Jiang and Tang (2017) [87]	GR	China	Cube	E & S	Summer	Yes	(√ - √ - √ - √ - √)	(√ - √ - 0)	HR,ES	–
Li et al. (2017) [88]	GR	Taiwan	Building	F	Summer	No	(√ - 0 - 0 - 0 - √)	(√ - 0 - 0)	–	–
Olivieri et al. (2017) [51]	GW	Spain	Building: office	F & S	Summer	Yes	(√ - √ - √ - √ - √)	(√ - √ - 0)	–	–
Ottelé and Perini (2017) [55]	GW, GF	Italy	Cube	E	Year	Yes	(√ - √ - √ - 0 - √)	(√ - √ - 0)	HR	–
Pérez et al. (2017) [89]	GW, GF	Spain	Cube	E	Summer	yes	(√ - 0 - √ - √ - √)	(√ - 0 - 0)	ES	–
Perini et al. (2017) [84]	GF	Italy	Building: office	F	Summer	yes	(√ - √ - √ - 0 - √)	(0 - √ - 0)	ES	–
Poddar et al. (2017) [85]	GW	South Korea	Building: dormitory, research, office	S	Year	yes	(√ - 0 - 0 - 0 - 0)	(0 - √ - 0)	HR,ES	–
Serra et al. (2017) [39]	GW	Italy	Cube	E	Year	yes	(√ - 0 - √ - 0 - √)	(0 - √ - 0)	HR	life cycle assessment
Basher et al. (2016) [16]	GF	Malaysia	Room	E	Summer	Yes	(√ - 0 - 0 - 0 - √)	(0 - 0 - 0)	–	–
Coma et al. (2016) [48]	GR	Spain	Cube	E	Year	Yes	(√ - √ - √ - 0 - √)	(√ - 0 - 0)	ES	
Pan and Chu. (2016) [40]	GW	China	House	E & F	Year	Yes	(√ - √ - √ - √ - √)	(0 - √ - 0)	ES	life cycle assessment
Silva et al. (2016) [77]	GR	Portugal	Building	E & F	Year	Yes	(√ - √ - √ - √ - √)	(√ - √ - √)	HR,ES	–
Šuklje et al. (2016) [52]	GF	Slovenia	Cube	E & M	Summer	Yes	(√ - √ - √ - √ - √)	(√ - √ - 0)	HR	–
Wong and Balbwin (2016) [53]	GF	China	Building	F	Summer	No	(√ - √ - 0 - 0 - 0)	(0 - √ - 0)	ES	–
Cameron et al. (2015) [65]	GF	UK	Cube	E	Winter	Yes	(√ - 0 - 0- 0 - √)	(√ - 0 - 0)	ES	–
Carlos (2015) [79]	LW	Portugal	Building	S	Winter	Yes	(√ - √ - √ - √ - 0)	(0 - 0 - 0)	ES	–
Flores et al. (2015) [90]	GF	Argentina	Model	S & M	Summer	yes	(√ - √ - √ - √ - √)	(√ - 0 - 0)	HR	–
Bolton et al. (2014) [70]	GF	UK	Building	E & F	Maritime	Yes	(√ - 0 - 0 - 0 - √)	(√ - √ - 0)	ES	–
Coma et al. (2014) [73]	GF	Spain	Cube	E & F	Summer	Yes	(√ - 0 - √ - 0 - √)	(√ - √ - 0)	ES	–
Feng and Hewage (2014) [41]	GR, LW	Canada	Building	S	Year	No	(√ - 0 - 0 - 0 - 0)	(0 - 0 - 0)	HR	Financial assessment
Feng and Hewage (2014) [38]	LW	Mediterranean countries	Building	S	Year	No	(0 - 0 - 0 - 0 - 0)	(0 - 0 - 0)	ES	Balance, emission
Haggag et al. (2014) [68]	LW	UAE	Building: School	F	Summer	Yes	(√ - 0 - 0 - 0 - √)	(√ - √ - 0)	ES	–
Malys et al. (2014) [42]	LW	Switzerland	Wall	E & M	Spring	No	(√ - √ - 0- 0 - 0)	(0 - 0 - 0)	HR	Plants performance
Mangone and van der Linden (2014) [81]	PP	The Netherlands	Building	F	Year	Yes	(√ - 0 - 0 - 0 - 0)	(0 - √ - √)	ES	Thermal comfort
Mangone et al. (2014) [62]	courtyard	Ghana	Building: Office	S	Tropical	Yes	(√ - 0 - 0 - 0 - 0)	(0 - √ - 0)	ES	Thermal comfort
Olivieri et al. (2014)^2 [60,91]	LW	Spain	Cube	E	Year	Yes	(√ - √ - √ - 0 - √)	(√ - √ - 0)	HR	–
Pulselli et al. (2014) [43]	LW	Italy	Building	S	Summer	Yes	(0 - 0 - 0 - 0 - 0)	(0 - 0 - 0)	ES	Emergy
Scarpa et al. (2014) [92]	LW	Italy	Wall	M	Year	No	(0 - √ - √ - 0 - √)	(√ - 0 - 0)	–	–
Tan et al. (2014) [44]	LW	Singapore	Wall	F	Monsoon	Yes	(√ - √ - 0 - 0 - √)	(√ - 0 - 0)	–	Radiant temp.
Chen et al. (2013) [69]	LW	China	Cube	E	Summer	Yes	(√ - √ - √ - 0 - √)	(√ - √ - 0)	ES	–
Jaafar et al. (2013) [76]	LW, GF	Malaysia	Building	E and F	Summer	No	(√ - √ - √ - √ - 0)	(√ - 0 - 0)	–	–
Mazzali et al. (2013) [80]	LW	Italy	Wall	E	Summer	Yes	(0 - 0 - √ - 0 - √)	(√ - 0 - 0)	HR	–
Nadia et al. (2013) [56]	LW	Algeria	Model	E	Summer	Yes	(√ - 0 - 0 - 0 - √)	(√ - 0 - √)	–	–
Susorova et al. (2013) [54]	GF	USA	Building	F and M	Summer	Yes	(√ - √ - √ - √ - √)	(√ - 0 - √)	HR	–
Tseng et al. (2013) [61]	LW	Taiwan	Wall	F and S	Year	Yes	(0 - 0 - 0 - 0 - √)	(0 - √ - 0)	ES	–
Varini (2013) [74]	LW	Colombia	Room	S	Summer	Yes	(√ - 0 - 0 - 0 - √)	(0 - √ - 0)	–	–

(continued on next page)

Table 1 (*continued*)

References	Types of greenery systems	Location	Space	Types of study	Season	W/O plant	Parameters			
							Outside (T_o - RH_o – SR – WS - T_{se})	Inside (T_{si} - T_i - RH_i)	Energy	Others
Fernandez-Bregon et al. (2012) [45]	LW	Spain	Wall	E	Spring	Yes	(√ - 0 - 0 - 0 - √)	(0 - 0 - 0)	–	Pressure sound
Fernandez-Canero et al. (2012) [34]	LW	Spain	Building: school	E	Summer	No	(√ - 0 - 0 - 0 - 0)	(0 - √ - √)	ES	–
Rodgers et al. (2012) [82]	BW	USA	House	E and F	Summer	No	(0 - 0 - 0 - 0 - 0)	(0 - 0 - 0)	ES	–
Pérez et al. (2011)^2 [46,93]	GF	Spain	Building	E	Year	Yes	(√ - √ - √ - 0 - √)	(0 - 0 - 0)	–	Illuminance
Perini et al. (2011) [94]	GF, LW	The Netherlands	Wall	F	Summer	Yes	(√ - 0 - 0 - √ - √)	(0 - 0 - 0)	–	–
Sunakorn and Yimprayoon (2011) [10]	GF	Thailand	Building: shopping mall	E and F	Summer	Yes	(√ - 0 - 0 - 0 - 0)	(0 - √ - 0)	–	Indoor air velocity
Cheng et al. (2010) [57]	GF	China	Building: office	E	Summer	Yes	(√ - √ - 0 - 0 - √)	(√ - √ - 0)	HR	–
Wong et al. (2010) [71]	GF, LW	Singapore	Wall	E	Monsoon	Yes	(√ - 0 - 0 - 0 - √)	(√ - 0 - 0)	–	–

Types of Greenery systems: GR … Green Roof, LW … Living Wall, GF … Green Façade, PP … Potted Plants, BW … BioWall. **Location:** country name. **Types of study:** E … Experimental, S … Simulation, M … Mathematical modeling, F … field measurement. **Season:** Sum … Summer, Win … winter, Year … whole year. **Parameters:** outside: (T_o outdoor air temperature – RH_o outdoor relative humidity – SR solar radiation – WS wind speed – T_{se} external wall surface temperature); insides: (T_{si} internal wall surface temperature – T_i indoor air temperature – RH_i indoor relative humidity); **Energy:** ES … energy saving, HR … heat flux reduction. NA … not available. U … overall thermal conductivity through walls. **Results:** TR … temperature reduction, RH … Relative humidity. **Results:** IS … insulated, ave … average value, max … maximum value, Δ_t … indoor temperature difference, Δ_r … indoor relative humidity difference, w/p … with plants, w/o … without plants, ↓ … reducing, ↑ … increasing, +ve … decreasing, -ve … increasing.
Superscript: 2 … two articles. **Subscript:** ex … external walls, in … internal walls, w/p … with plants, w/o … without plants.

Table 1 provides necessary information mentioned in articles: types of greenery systems, location and environment, type of study, season, providing a comparison to without plants, and parameters, each of which is discussed, while Table 2 provides the primary findings for each article. This review paper considers any experimental and field study with specific criteria that can be summarized in Fig. 2.

3. Results

Plants have been used outdoors as the vegetated cladding of buildings, which are defined as greenery systems. Three major types of greenery system are green facades, green walls, and green roofs. Green façade can be classified as direct or traditional façades, where plants are attached directly to the walls, and indirect or double skin façades, which include continuous guides or modular trellis for a vertical support structure for plant climbing. Living walls or green walls have two main types: continuous green walls by using a continuous screen or geotextile felt, and modular green walls by using trays, vessels. Green roofs have three types as intensive, semi-intensive, and extensive green roofs [2], as shown in Fig. 3.

Table 1 shows general information and types of greenery system, location, type of the conducted space, and the period of the study, and the studied parameters. There are 56 articles studied in 2010 to early 2019. Most publications are conducted in 2017 with 15 articles, then 2014 and 2013 with 12 and seven articles, respectively, as shown in Fig. 4. Most of the studies have focused on the green wall system in 23 articles than on the green façade in 16 articles, and green roof system in 5 articles during the selected period, as illustrated in Fig. 4. There are some studies, which combined two systems such as green wall and green façade and green wall and green roof system.

The locations of studies were varied over all over the world. China and Spain have the highest number of publications as nine articles followed by Italy, which have eight articles, as graphed in Fig. 5. Also, the continent of Europe has conducted the highest research reaching to 27 articles on greenery systems followed by continent of Asia which contributed to 20 articles, then continent of North America (4 articles), the continent of Africa (3 articles), and the continent of South America (2 articles).

The conducted space can be classified into buildings, such as office building, shopping mall, supermarket, school, university campus, and hospital, model as in the simulation modeling for a space, cube of bricks or steel, a separate wall, a whole house, and a room. Fig. 6 shows the no of conducted articles on buildings are the highest number reaching to 24 articles, then on cubes (14 articles) and walls (7 articles). Also, Fig. 6 shows the distribution of the conducted season, which the summer season (25 articles) was the most conducted period for research following by the whole year research period (20 articles). Studies have also considered the effect of greenery systems in winter and spring season. Other studies have been conducted in constant weather over the year with a slight change such as tropical, monsoon, and maritime.

A comparison between a building structure with and without greenery systems has also reviewed in Table 1. "Yes" in the table refers to that there is a comparison, and "No" refers to that the bare wall or roof was not part of the study. This comparison is useful in understanding and estimating the effect of adding greenery systems on the building structures. According to Fig. 7, a comparison between with and without plants have been implemented in major studies (44 articles), while 12 articles have focused on with greenery systems only, as shown in Fig. 7 and. Also, the types of studies conducted are experimental studies (E), field measurements (F), simulation (S), and mathematical modeling (M). The experimental studies have been performed on cubes and walls and found in 21 articles, and ten articles are combined between experimental and others. The field studies represent the measurements in actual buildings and house as well as in simulation studies. The mathematical modeling considers governing equations of heat transfer through the building envelope and walls. The field and

Table 2
Results from previous research related to Table 1.

References	Building Envelope U ($W/m^2.K$)	Outdoor Environment		Microclimate		Indoor conditions	# occupants	Results
		T_o (°C)	RH_o (%)	TR_{ex} (°C)	TR_{in} (°C)	T_i (°C) or RH_i (%)		ES (%) or HR (%)
Xing et al. (2019) [75]	Steel and Insulation, $U_{w/o} = 1.09$	0 to 12	70 to 80	15 ↓ day −3↑ night	5 ↓ day −3↑ night	w/o: 1 to 27 w/p: 4 to 21, RH_i 45% $\Delta_t = 9$ ↓	0	HR: 20 ↓ ES: 18 ↓
Pan et al. (2018) [49]	polystyrene and double gypsum boards, $U_{w/o} = 0.990$, $U_{w/p} = 0.621$	25.7 to 42.6	78	0.9 to 6.1 ↓	NA	w/p: 27.9 to 34.6, W/o: 28.0 to 39, $\Delta_t = 8.2$ to 3.6 ↓	0	HR: 12.4 to 41.6 ↓
Vox et al. (2018) [63]	south walls: masonry bricks with mortar plaster coating, The rest walls: expanded polystyrene, $U_{w/o} = 1.224$ to 1.233	sum:15 to 41.7 win: 0.9 to 18	ave. 78	sum: 2 to 7 ↓ win: −2.5 ↑to 5 ↓	NA	NA	0	–
Widiastuti et al. (2018) [72]	reinforced concrete, brick walls, asbestos gable roof, $U_{w/o} = 0.31$	24.6 to 26.0	62.90	2 to 13 ↓	4 to 10 ↓	w/o:26.4, w/p: 24.6 RH_i: 72.5%	0	HR: 60 to 97 ↓
Yuan and Rim (2018) [47]	$U_{w,w/o} = 0.89$ to 1.31, $U_{w,w/p} = 0.71$ to 0.953, $U_{r,w/o} = 0.41$ to 0.57, $U_{r,w/p} = 0.37$ to 0.49	ave. 24.3	72.30	NA	NA	NA	0	ES_{GW}: 5 to 72↓, ES_{GR}: 15 to 85 ↓ .
Bianco et al. (2017) [50]	wood, polystyrene insulation, plaster coating, $U_{w/o} = 0.4$, $U_{w/p} = 0.17$	sum: 23.8 to 31 win: 5 to 14	NA	sum: 7 to 23↓ win: 2 to 8↓	NA	sum: 23.1 win: 23.4	0	HR_{sum}: 56 to 63.3↓ HR_{win}: 37 to 44 ↓
Coma et al. (2017) [67]	reinforced concrete slab, concrete walls, roof of extruded polystyrene, plaster precast concrete beams, ceramic flooring	sum: 17 to 42 win: −4 to 12	NA	Sum: GF: 17 to 21.5 ↓ GW: 10.7 to 13.9 ↓ Win: GF: −0.3 to 0.7 ↓ GW: 4.5 to 16.5 ↓	Sum: GF:1 ↓ GW: 1 to −3 ↑ Win: NA	sum: 18 to 24 win: 22	0	Cooling: ES_{GW}: 31 to 39 ↓, ES_{GF}:5 to 34 ↓ Heating: ES_{GW}: 2.9 to 4.2 ↓, ES_{GF}: −0.36 to 1.9 ↓
Cuce (2017) [86]	brick walls	8 to 16	75–84%	4 to 6	2.5	NA	NA	HR: 43 ↓
Dahanayake et al. (2017) [83]	brick walls	32.8	81%	5 to 12.3	NA	24	4422 persons	cooling ES: 0.4 to 1.8 ↓annual, sum 34 ↓
Dahanayake and Chow (2017) [64]	sum: brick insulated wall, $U_{w/o} = 0.25$. win: steel stud construction, gypsum board, glass wall	sum: ave 38.7 win: ave −3.9	NA	sum: 4.8 to 26.2 win: ave 16.9	NA	sum: 24 win: 20	NA	Cooling ES: 2 to 3 ↓ Heating ES: 0.3 to 2 ↓
Foustalieraki et al. (2017) [66]	Insulated heavyweight reinforced concrete roof,	sum: NA winter ave: 16 to 19	NA	sum: NA Win: 21.9 ↓	NA	sum: 25, $\Delta_t = 0.1$ to 1.1 ↓ win: 20, $\Delta_t = 0.1$ to 0.7 ↑	NA	Cooling: ES: 18.7 ↓ Heating: ES: 11.4 ↓
Haggag et al. (2017) [37]	hollow concrete block, stucco	ave: 46	NA	12 to 14 ↓	3 ↓	w/o: 47, w/p: 39, Δ_t: 8 ↓	NA	HR: 24 ↓, ES: 12 ↓
Jiang and Tang (2017) [87]	Concrete slab, $U_{r,w/o} = 0.62$, $U_{r,w/p} = 0.48$, polyethylene insulation brick walls, $U_{w,w/o} = 1.90$	33 to 43	ave: 78	14 ↓	5 to 8 ↓	w/o: 24 to 37, w/p: 25 to 32, $\Delta_t = 3$ to 5.7 ↓	0	HR: 75–79 ↓ ES: 10.3–24.6 ↓
Li et al. (2017) [88]	concrete roof	27 to 42	NA	$T_{ex,w/p}$: 29 to 38	$T_{in,w/p}$: 30 to 32	NA	NA	–
Olivieri et al. (2017) [51]	galvanized steel, extruded polystyrene, $U_{w,w/o} = 0.89$ $U_{w,w/p} = 0.37$ to 1.42	20 to 32	20 to 52	$T_{ex,w/p}$: 11.7 to 23.6	$T_{in,w/p}$: 17.5 to 23.3	w/p: 18.6 to 25	0	–
Ottelé and Perini (2017) [55]	brick, mineral wool, limestone, $U_{w/o} = 0.299$, GF: $U_{w/p} = 0.24$ to 0.28, GW: sum $U_{w/p} = 0.03$ to 0.078, win $U_{w/p} = 0.21$ to 0.22	sum:34.8 win: −7.6 to 2.1	sum: 85	sum: GF:1.7 ↓ GW: 5.8 to 8.4 ↓ win: NA	sum: GF: 0.4 ↓, GW:0.9 ↓ win: GF:1.5 ↑ GW: 2.3↑	sum: w/o:24.1, w/p:23.1 to 24.4 win: w/o:17.9, w/p: 19.9 to 20.1	0	–
Pérez et al. (2017) [89]	gypsum, alveolar insulated brick, cement mortar coating, $U_{w/o} = 0.784$	17 to 38	NA	10.1 to 16.4↓	2.5↓	NA	0	ES: 34 annual ↓
Perini et al. (2017) [84]	masonry brick, polystyrene insulation, $U_{w/p} = 0.44$	17 to 42	NA	8 ↓	NA	25	18 persons	ES: 26.5 ↓
Poddar et al. (2017) [85]	NA	sum: 22 to 30 win: −2.5 to 10	NA	NA	NA	sum: 24 win: 18 to 22	Dormitory: 600 students NA-research & office	HR: 10 to 40 Heating ES:1 to 62.5 ↓ Cooling: ES: 1.5 to 25 ↓
Serra et al. (2017) [39]	plasterboard, extruded polystyrene insulation, wooden cladding, $U_{w/o} = 0.25$ to 0.40, $U_{w/p} = 0.17$ to 0.29	win: 6 to 14, sum: 19 to 32	NA	sum: 6 to 10↓, win:2 to 6 ↑	NA	w/p: 24.0, w/o: 28.5, $\Delta_t = 4.5$ ↓	0	Heating: HR: 65 ↓
Basher et al. (2016) [16]	brick and metal deck roofing	29 to 42	–	0.7 to 6.4 ↓	NA	NA	0	NA
Coma et al. (2016) [48]	Concrete $U_{w/p} = 0.79$ to 1.4 $U_{w/o} = 0.71$ IS	4 to 24	51 to 80	–	0.5 to 1	18 and 22	0	ES: 2–19↓
Pan and Chu. (2016) [40]	NA	28 to 33	78	1 to 8↓	–	w/o: 28, w/p: 25.5	0	ES: 13.6 to 18.3 ↓

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Table 2 (*continued*)

References	Building Envelope U (W/m^2.K)	Outdoor Environment		Microclimate		Indoor conditions	# occupants	Results
		T_o (°C)	RH_o (%)	TR_{ex} (°C)	TR_{in} (°C)	T_i (°C) or RH_i (%)		ES (%) or HR (%)
Silva et al. (2016) [77]	concrete slab, beams roof	sum: 28 to 40 win: 6 to 15	sum:60 win: 83	NA	$T_{in,w/p}$: 28 to 29	sum: 24- RH_i: 50% win:19- RH_i: 50%	0	Cooling: ES: 45 to 70↓ Heating: ES: 20 to 60↓
Šuklje et al. (2016) [52]	Concrete wall, $U_{w/o} = 1.67$, $U_{w/p} = 0.082$,	18 to 36	84	two-layers: 34 ↓ one-layer: 29 ↓	NA	23.5	0	HR: 77 ↓
Wong and Balbwin (2016) [53]	Concrete wall, $U_{w/o} = 0.74$, $U_{w/p} = 0.18$	26 to 31	75	NA	NA	24	NA	ES: 76 ↓
Cameron et al. (2015) [65]	Brick	ave 2	–	−1.3 ↑	–	–	0	ES: 30↓
Carlos (2015) [79]	Only support $U_{w/p} = 0.37$ $U_{w/o} = 2.15–3.25$	2 to 24 ave 4	55 to 90	–	–	–	0	ES: 10↓
Flores et al. (2015) [90]	massive brick wall, expanded polystyrene insulated, galvanized iron, $U_{w/o} = 6.67$	ave: 28.3 max: 38.4	71%	1 to 2 ↓	1.3 to 2 ↓	NA	0	HR: 30 to 60 ↓
Bolton et al. (2014) [70]	Brick, $\mathbf{U_{w/o}} = 4.18$	−2.2 to 17.4	–	3.1 ↓	0.1 ↓	20	0	ES: 8↓
Coma et al. (2014) [73]	Concrete	15 to 35	–	10 ↓	−0.5 ↑	24, 14 to 20 $\Delta_t = 0.2$↓	0	ES: 1, 5.5↓ cumulative
Feng and Hewage (2014) [41]	NA $U_{w/p} = 0.32$	−7 to 20	–	–	–	17–27	0	HR: 0.6–5.4 GR↓ 2.1–8.4 LW↓
Feng and Hewage (2014) [38]	Only support	–	–	–	–	–	0	ES: 1.2 to 43↓
Haggag et al. (2014) [68]	Concrete	35 to 50 sum 25 to 35 win	–	7↓	6↓	47 w/p, 55 w/o Δ_t = +8↓	NA	ES: 20.5↓
Malys et al. (2014) [42]	Brick	7 to 15	50 to 95	5 to 10 ↓ 3 to 7 ↓	–	–	0	–
Mangone and van der Linden (2014) [81]	Wall assembly, $U_{w/o} = 0.14$ to 0.35 IS	25 to 27	–	–	1.1 to 2 ↓	25 to 28 w/p	Occupied	ES: 2.9 to 9.5↓
Mangone et al. (2014) [62]	NA	< 5	–	–	–	21.5, 22 RH_i: 42.71 9.7% comfort high	67 persons	–
Olivieri et al. (2014) [91]	NA, $U_{w/o} = 0.33$ IS $U_{w/p} = 0.37$ IS	20 to 30 sum 4 to 8 win	20 to 40 sum 60 to 80 win	15 ↓ −2 to 0 ↑	8 to 11 ↓ 2 to 7 ↓	Δ_t = 2 to 10↓	0	–
Olivieri et al. (2014) [60]	NA, $U_{w/o} = 0.33$ IS $U_{w/p} = 0.37$ IS	ave 25.1	27 to 57	7 ↓	8 ↓	23.2 w/p, 27.4 w/o Δ_t = 4↓	0	HR: in 93↓ out 98↓
Pulselli et al. (2014) [43]	Bricks $U_{w/o} = 0.21$ IS, 1.13	–	–	–	–	–	0	ES: 6.2 to 15.2↓
Scarpa et al. (2014) [92]	Concrete, brick	–	–	–	–	–	0	–
Tan et al. (2014) [44]	Concrete	23 to 32	ave 76	9 ↓	0.5 ↓	–	0	–
Chen et al. (2013) [69]	Brick $U_{w/p} = 0.25$	28 to 46	45 to 98	21 ↓	max 7 ↓	37 w/p, 38.5 w/o Δ_t = +1.5↓	0	ES: 12↓
Jaafar et al. (2013) [76]	Only support	24 to 46.7	ave 70.2	–	1 ↓	RH_i: 70–72 Δ_r = ave 2↑	0	–
Mazzali et al. (2013) [80]	Concrete	–	–	1 to 20 ↓	–	–	0	HR: in 13–70↓ out 3–80↓
Nadia et al. (2013) [56]	Brick, Concrete	28 to 57	–	0.8↓	21↓	RH_i: 41.5 w/p, 47.4 w/o, Δ_r = +6↓	0	–
Susorova et al. (2013) [54]	Brick, $U_{w/o} = 4$ $U_{w/p} = 2.5$	22 to 38.8	55 to 83	1.2↓	0.6↓	–	0	HR: 14 to 43↓
Tseng et al. (2013) [61]	Concrete	–	–	2.2↓	–	22.3 w/p, 23.9 w/o Δ_t = +1.6↓	Occupied	ES: 7 to 10↓
Varini (2013) [74]	Brick	24 to 32	–	5.5↓	–	Δ_t = +1.8 to 6↓	0	–
Fernandez-Bregon et al. (2012) [45]	Concrete	10.9 to 21	–	5↓	–	–	0	–
Fernandez-Canero et al. (2012) [34]	Only support	18 to 36	–	–	–	w/p: 19–22 w/o: 21–26 Δ_t = +4↓	0	ES: 20↓
Rodgers et al. (2012) [82]	NA	–	–	–	–	–	0 & 1 to 20 persons	ES: 27↓
Pérez et al. (2011) [46]	NA	7 to 33	25 to 65	5.5 to 15.8 ↓	–	–	0	–
Pérez et al. (2011) [93]	NA	20 to 32	ave 44	7 to 15.2 ↓	–	–	0	–
Perini et al. (2011) [94]	Brick and plywood	13 to 32, ave 16	–	2.7 GF ↓ 5 LW ↓	–	–	0	–

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Table 2 (*continued*)

References	Building Envelope U (W/m^2.K)	Outdoor Environment		Microclimate		Indoor conditions	# occupants	Results
		T$_o$ (°C)	RH$_o$ (%)	TR$_{ex}$ (°C)	TR$_{in}$ (°C)	T$_i$ (°C) or RH$_i$ (%)		ES (%) or HR (%)
Sunakorn and Yimprayoon (2011) [10]	NA	ave 34.25 ave 32	–	–	–	w/p: 28–33 w/o: 27–36 Δ_t = +1.65 to 4↓	0	–
Cheng et al. (2010) [57]	Concrete	ave 26.4	ave 75	2 to 16 ↓	1 ↓	25.2	0	HR: 85↓
Wong et al. (2010) [71]	Concrete	25 to 34	–	7 to 12 ↓	–	–	0	–

simulation studies are conducted on nine articles each and mathematical modeling are conducted in one article alone and two articles combined with simulation and experimental and one article combined with field studies.

Fig. 8 shows the number of publications for each parameter. The ambient air and the external surface temperature are recorded the highest number of articles (51 and 42 articles, respectively). The least measured parameter was the indoor relative humidity (RH$_i$), and 28 articles have produced results of six parameters as T$_o$, RH$_o$, SR, T$_{se}$, T$_{si}$, and T$_i$. The results for energy saving and heat reduction are found in 23 and 15 articles, respectively.

Furthermore, other parameters also were included, such as financial assessment [37,38], life cycle assessment [39,40], energy balance and emissions [41], the performance of plants [42], emergy, which is environmental accounting method that evaluate the energy consumed in direct and indirect transformations [43], radiant temperature of outdoor air [44], sound pressure [45], illuminance [46], and the indoor air velocity [10].

3.1. *Building structure*

The building envelope was constructed of concrete or brick. As shown in Table 2, 12 studies have stated the thermal conductivity for the building envelope with and without greenery systems. The wall and roof structure vary among brick, concrete, gypsum board, and steel structure.

The green roofs have reduced the thermal conductivity of office, hospital, and school buildings from 0.41 to 0.37 W/m^2.K and 0.57 to 0.49 W/m^2.K with a reduction of 9.8–14% [47]. Also, a constructed cube with a concrete slab covered with an extensive green roof has decreased the thermal conductivity from 0.62 to 0.48 W/m^2 K by a reduction of 22.5%. In another study, three cubicles were built with three roof construction [48]: a conventional flat reference roof with insulation; an extensive green roof with pozzolana drainage layer; and an extensive green roof with rubber crumbs drainage layer. The reference design has a thermal conductivity of 0.71 W/m^2.K, while the two designs have a thermal conductivity of a range of 0.79–1.4 W/m^2.K with an increase of 11.3–97%. This increase is a result of the retention of moisture in the roof soil. However, adding a green roof saved the energy consumption of the cubicle by 2–19% over the year [48].

The green or living walls have been constructed on an insulated gypsum board, causing a reduction of thermal conductivity from 0.99 to 0.621 W/m^2 K by 37% [49]. Similarly, a cubicle made of wood wall and insulated with polystyrene has thermal conductivity of 0.4 W/m^2.K, and a modular felt green wall was added causing a reduction of the thermal conductivity to 0.17 W/m^2 K by 57.5% [50]. Also, an external isolated (3-cm extruded polystyrene) steel wall for an office has a thermal conductivity of 0.89 W/m^2.K [51]. Three modular felt walls have been constructed and investigated. The first green wall has with no insulation with a thermal conductivity of 0.37 W/m^2.K, the second and third green walls have a 3-cm and 7-cm extruded polystyrene insulation and have thermal conductivity of 0.64 and 1.42 W/m^2.K, respectively [51]. This results in a reduction of 28% for the same insulation width and an increase of 60% for 7-cm insulation.

Moreover, the green façades have reduced the thermal conductivity of a concrete wall of a cubicle from 1.67 W/m^2.K to 0.082 W/m^2 K by a reduction of 95% [52]. Also, the green façade was designed on a concrete wall of an office building with thermal conductivity of 0.74 W/m^2.K causing a reduction of thermal conductivity to 0.18 W/m^2 K by 76% [53]. Besides, a green façade has covered a brick wall of an office building yielding a reduction of thermal conductivity from 4 to 2.5 W/m^2 K by 37.5% [54].

Hence, the climbing plants add thermal resistance to the uninsulated wall and roof structure, resulting in reducing the overall thermal, and they can reduce the amount of heat transfer through vegetated walls and green roofs. However, the reduction of thermal

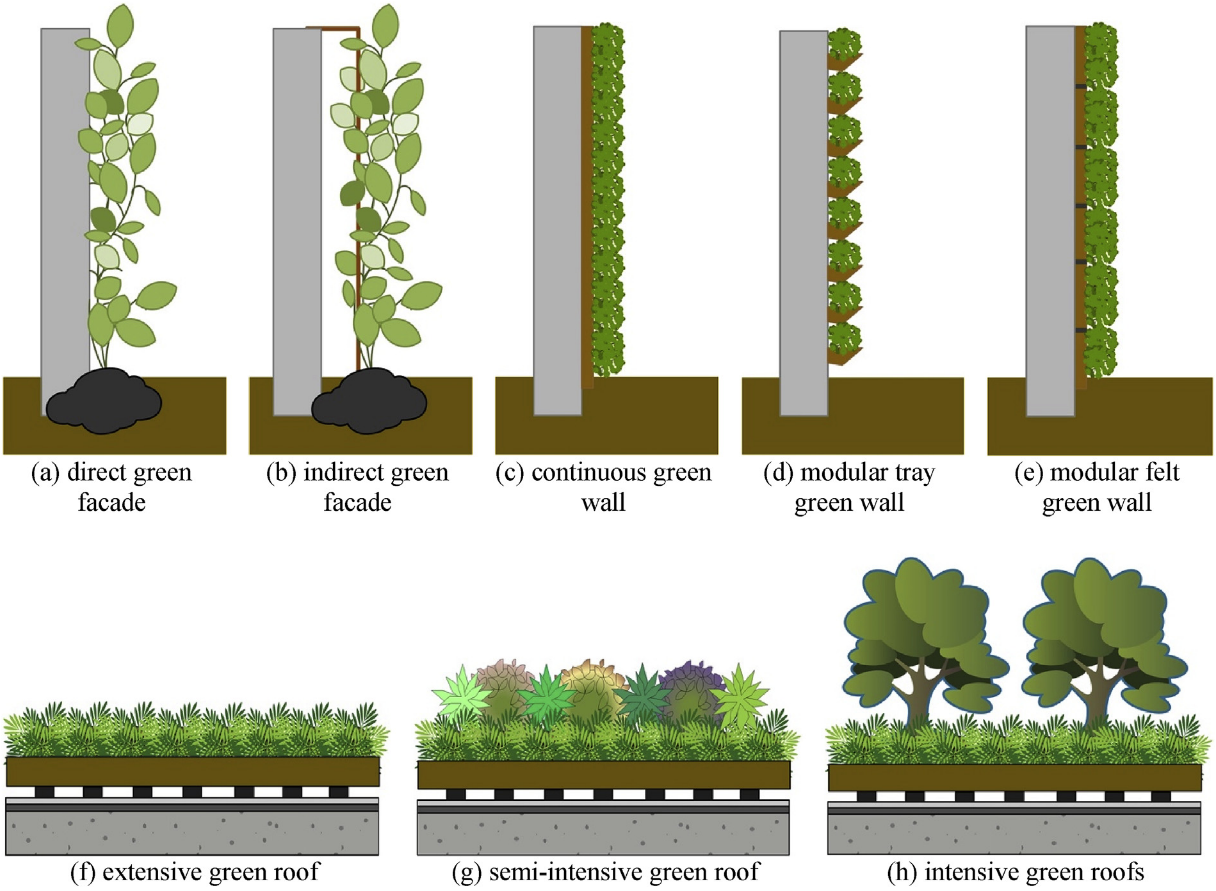

Fig. 3. Types of greenery systems [2,19,36].

conductivity may vary according to the building structure and the weather change [55].

3.2. Outdoor environment conditions

Both outdoor air temperature and relative humidity were measured in 24 articles. According to the locations, there are low average values of air temperatures in winter seasons (e.g., 2 °C, 4 °C, and 9 °C), and high ranges of temperatures referred to summer seasons from 25 °C to 50 °C. The relative humidity varies according to the precipitation amount and has two levels: low level or dry to moderate weather from 25% to 50%, and high level of precipitation from 50% to 90%. The solar radiation varies from 230 W/m^2 to 750 W/m^2 [44,56,57]. The effect of greenery systems on outdoor conditions have been investigated. For example, vertical greenery systems can provide a cooling effect in a cold and semi-arid climate such as Tehran, Iran [58]. The ambient temperature of green covered buildings was cooler in summer and winter than that of bare buildings. Another example, the impact of the green façade and green wall on the urban environment has been examined in a tropical area such as Indonesia [59]. Green façade and green walls have reduced the outdoor temperature by 1.2 and 0.3 °C, respectively, which mitigate urban heat island effect.

3.3. Microclimate conditions

The microclimate conditions refer to temperature differences of external and internal wall surfaces between envelopes with and without vegetation. This comparison will demonstrate the effect of using greenery systems on energy saving due to temperature reduction, as shown in Fig. 3. The circumstances vary according to the building envelope, the location of the system, the variation of environmental conditions, and the greenery system designs, which leads to variation in

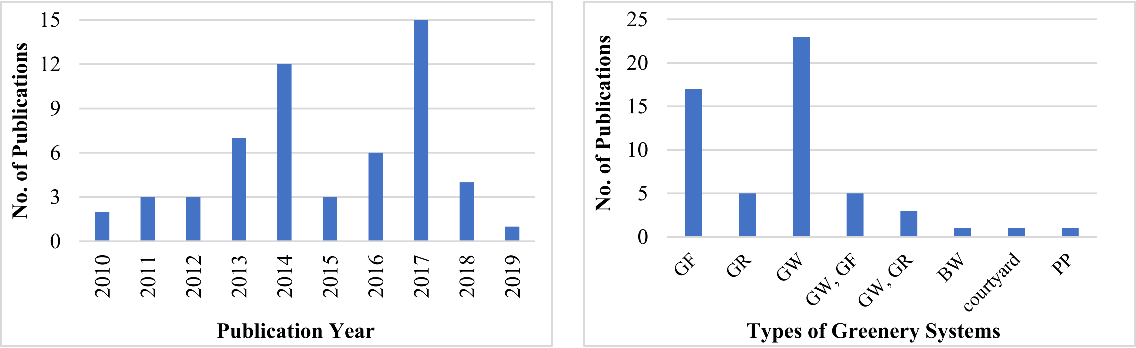

Fig. 4. The publication year and the types of the greenery systems in the captured articles.

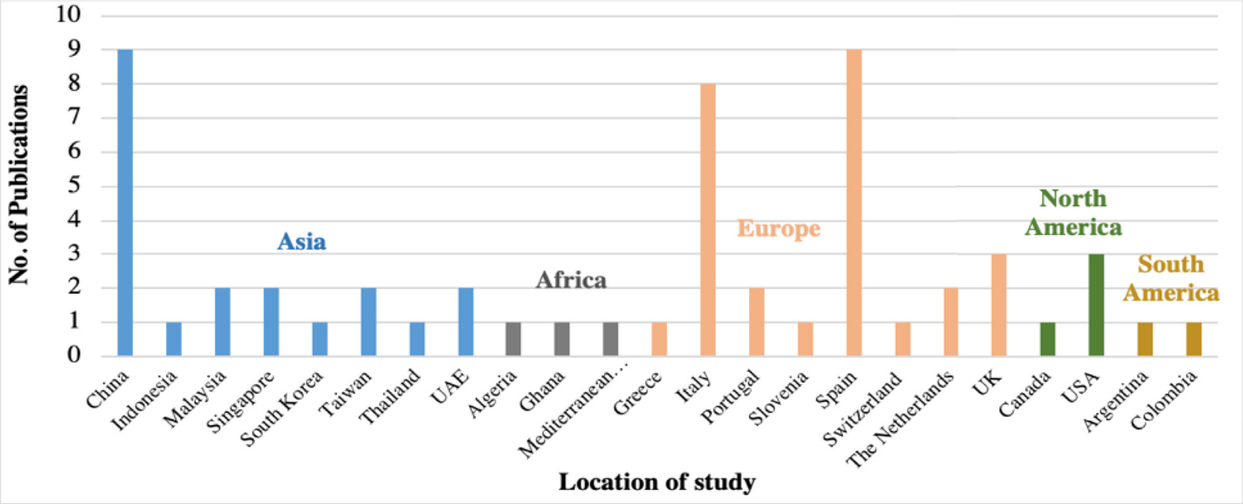

Fig. 5. The locations of the conducted studies during the selected period.

values of temperature reduction for both external and internal surface temperatures as in equations 1 and 2.

As shown in Table 2, the temperature reduction for external surfaces varied between −2 °C and 15 °C [60] and 5.5 °C–15.8 °C [46] over the year because of the change in weather and the fluctuation of solar radiation. This reduction was significant in studies without human occupancy. However, in a field study with human occupancy, Tseng et al. [61] observed that the external temperature reduction was 2.2 °C during the year by applying a large vertical garden on one wall. For the internal surfaces, the temperature reduction changed based on the location of greenery system and the occupancy number; for empty places, 0.5 °C–1 °C for green roofs [48], 2 °C–11 °C for living walls [60]. Mangone et al. [62] investigated the use of potted plants inside an office with occupants resulting in reducing the internal surface temperature by 1.1 °C–2 °C.

3.3.1. Winter season

During the winter season, four studies have conducted in Italy [39,50,55,63], one study in China [64], one in the UK [65], one in Greece [66], and one in Spain [67]. The external temperature reduction (TR_{ex}) was varied from 5 to 10 °C and an increase in the vegetated wall surface temperature by 0.3–2.5 °C [63,65,67]; the negative values of external temperature reduction means that the green wall is warmer than the bare wall, which means the wall surface behind the vegetation is warmer, for instance, the minimum of −0.3 °C [67] and −2.5 °C [63] during the night of the winter season for green façade. That is because the vegetation acts as insulation during the winter season to protect the wall from the cold weather. Foustalieraki et al. [66] obtained the highest external temperature reduction of 21.9 °C by using different plants species in the intensive green roof system. This reduction leads to 11.4% saving in heating load. However, Dahanayake and Chow [64] obtained high external temperature reduction reaching to 16.9 °C in China (Hong Kong and Wuhan), but the saving in heating load was 0.3–2% less than the previous study by constructing green wall system. The overall thermal conductivity of the vegetated wall is less than the bare wall resulting in saving heating load during cold weather.

3.3.2. Spring and summer season

During spring and summer seasons, the solar radiation and the ambient air temperature significantly raise resulting in increasing the external surface temperature more than the outdoor air temperature by about 5–10 °C due to the high absorptivity of the construction material. It was obvious that the temperature reduction for the external surfaces was higher than that of other seasons with a range from 2 °C to 20 °C. The high values were related to the exposure to peak solar radiation, which was absorbed by plants, and occurred during between 14 and 16 solar hour, while the low values were related to the reduction during the night or cloudy days. The majority of internal surface temperature reduction was about 1 °C. There are three high values: 6 °C [68], 7 °C [69], 21 °C [56] based on a room model. The reason for that, the design of experimental space was tight, mostly without windows, insulated space, and without occupation, which exposed to extremely high outdoor air temperature more than 45 °C.

3.3.3. Other seasons

In Maritime season, the outdoor air temperature ranged from −2.2 °C to 17.4 °C [70], the temperature reduction was an average of 3.1 °C for external surfaces and of 0.1 °C for internal surfaces. The use of vegetated walls helped damp the oscillation of surface temperature and relatively increased wall temperature in freezing weather, as well as

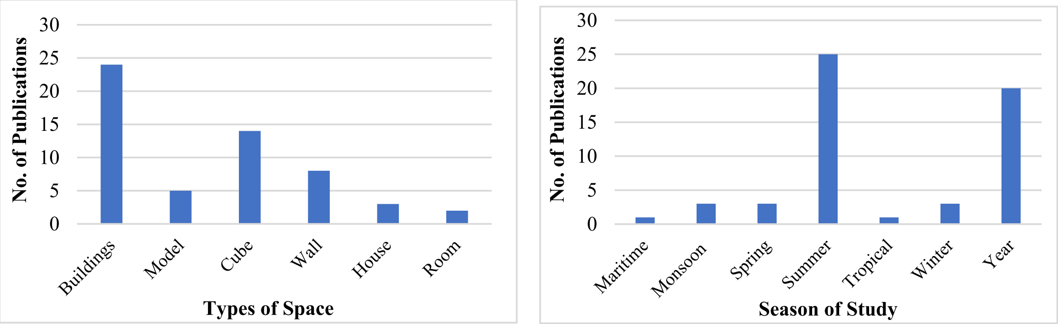

Fig. 6. The types of conducted space and the conducted season of the studies.

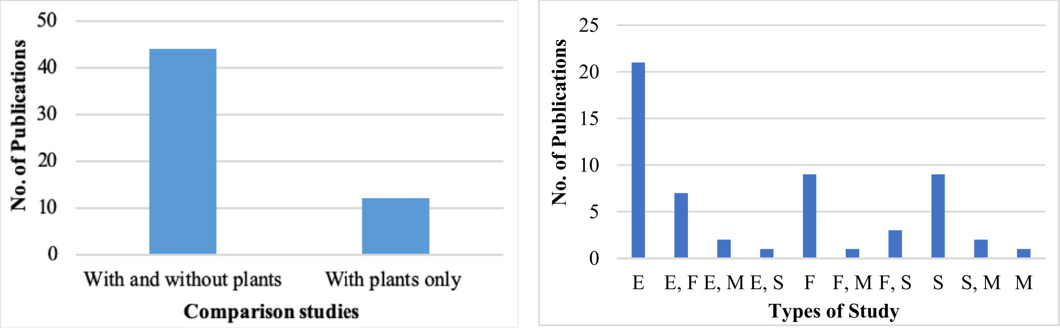

Fig. 7. The comparison studies and the types of conducted studies during the selected period.

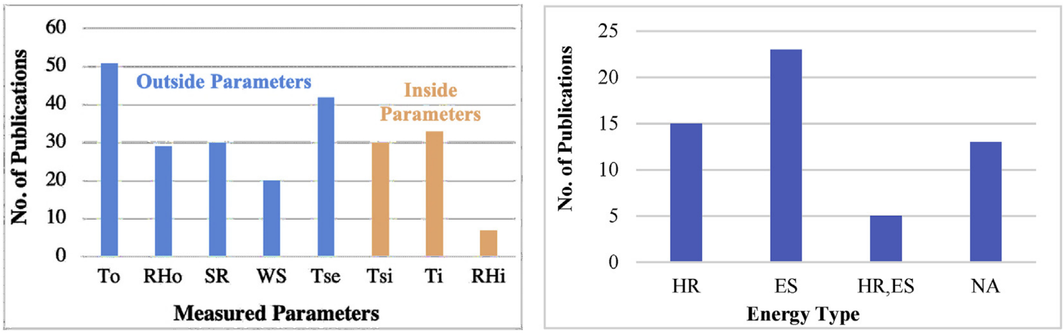

Fig. 8. The measured parameters and the type of energy in the captured articles.

decreased wall temperature in high ambient temperature compared to bare walls.

In the monsoon season, three studies have investigated the greenery system in monsoon season in Singapore [44,71] and Indonesia [72]. The external wall temperature was reduced by an average of 9 °C, while the interior wall temperature was reduced by 0.5–10 °C. The total heat transfer through the building envelope was reduced by 60–97% [72].

Mangone et al. [62] have investigated the effect of a courtyard on an occupied office building in the tropical season in Ghana. There was no information regarding the external and internal surface wall temperatures. However, the courtyard achieved better thermal comfort by 9.7% compared to an unvegetated building.

3.4. Indoor conditions

Indoor conditions are mostly indoor air temperature and relative humidity, and they can be divided into air-conditioned and unconditioned spaces. For the air-conditioned space, as shown in Table 2, the indoor air temperature has two levels: constant at different setting temperatures and free-floating temperature. First, the constant temperatures have different values, such as 18 °C, 22 °C, 24 °C, and 25.2 °C. The thermal comfort of an office with indoor plants was improved by 9.7% compared to an office without plants [62] based on the mean predicted votes of satisfied occupants. Second, the free-floated temperatures have different ranges, such as 14 °C–20 °C [73] with a reduction of 0.2 °C, 17 °C–27 °C [41], 25 °C–28 °C [62], 23.9 °C with a reduction of 1.6 °C with green walls [61], and 19 °C–22 °C and 21 °C–26 °C with a reduction of 4 °C [34].

For unconditioned space, two indoor conditions were compared when the door of the studied space was opened and closed. A space with a green façade covering a window caused the indoor air temperatures changed from 27 °C to 36 °C without plants to 28 °C–33 °C with green façade by a decrease of 1.65 °C–4 °C [10]. For the rest of the studies, the indoor temperature reduction was varied according to room size and weather conditions. Haggag et al. [68] measured the indoor air temperature inside an unconditioned school. They found that the temperatures would be 55 °C without plants and dropped to 47 °C with living walls since the outdoor air temperature ranged from 35 °C to 55 °C in summer. Still, the use of air conditioning systems is essential since the indoor air temperature is above the comfort zone (22 °C–26 °C).

In the arid and hot climates, the use of living walls dropped the indoor air temperature to 37 °C by a difference of 1.5 °C compared to the bare walls [69]. This temperature reduction is not sufficient to make the occupants feel thermally comfortable since the temperature is out of the range of 22–26 °C for thermal comfort. However, in moderate climates, the outdoor air temperatures have a maximum value of 30 or 32 °C, and the indoor air temperature is reducing by 2–10 °C and 4 °C [60], and 1.8–6 °C [74], which is likely to provide thermal comfort to the occupants.

Regarding indoor relative humidity, few studies have measured the indoor relative humidity as in Fig. 8. The indoor relative humidity was assumed to be 45% for modeling a building with a green façade [75]. In addition, the indoor relative humidity for a cuboid in Indonesia was recorded as 72.5% before adding the green façade and no records for a condition with a green façade [72]. However, the measured indoor relative humidity was 42.71% for a conditioned office with an improved in thermal comfort by 9.7% [62]. There are two studies that record difference in indoor relative humidity in both cases. Jaafar et al. [76] have constructed steel frames covered by green walls and green facades. The indoor relative humidity was recorded as 70% and 72% for a bare wall and vegetated walls, respectively, with an increased average value of 2% by using plants. Also, Nadia et al. [56] have built a small cube of brick and installed a continuous green wall. The indoor relative humidity was reduced from 47.4% to 41.5% with a difference of 6% by green walls. The variation of these values depends on the watering process and the evapotranspiration process of plants.

3.5. Heat reduction and energy savings

The vegetation on the building envelope works as external insulation, which may reduce energy demand. The energy saving relies on the

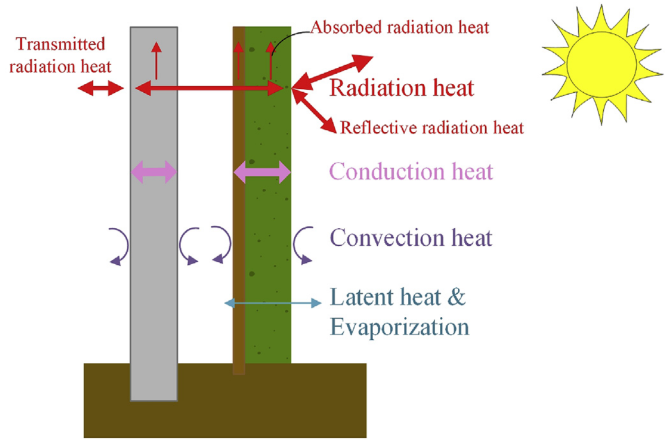

Fig. 9. Heat transfer modes in the greenery system.

heat transfer reduction through the envelope and the savings in energy consumption of a building or studied room. The heat transfer reduction and energy saving are calculated according to equations 3 and 4, respectively. Fig. 3 shows the heat transfer through the building envelope and energy use of the mechanical device in the building. There was temperature reduction through walls and environmental conditions; energy consumption was reduced in most studies with a range of 2–70%. The variation of results depends on the percentage of green coverage, the weather conditions, and the system design.

Buildings with green roofs consume less energy by 2–19% [48] and have less heat transfer by 0.6–5.4% [41] than that of bare roofs of a model house. The retention of moisture content in the soil may increase the indoor relative humidity and be a vital agent in cooling the roof in the summer and isolated the roof in the winter. Therefore, they can reduce building power consumption by 45–70% and 20–60% in the summer and winter season, respectively [77]. For a building with green facades, the energy saving was 5.5–30% for different seasons and can reach to high heat transfer reduction by 85% compared to a bare wall [57] while less energy saving during winter seasons [65,70]. However, the green façades and walls may increase the surface temperature of building envelopes in the winter season [78] yielding to reducing the building heating load by 10–30% as in [65,79]. For green walls, the average building energy saving was more than 10%, while the range is from 1.2 to 43%. Besides, most plant species used in research are evergreen and deciduous plants since they affect the heat transfer reduction by the percentage of vegetation coverage.

In comparison between greenery systems, Feng and Hewage [41] compared green roofs to living walls and found that the heat transfer reduction between green roofs and bare roofs (0.6–5.4%) is less than the heat transfer reduction between living walls and bare walls (2.1–8.4%). Additionally, the heat flux reductions were 93% and 98% for green roofs and living walls, respectively [60], and more than that of the green façade (85%) [57]. Other moderate heat reduction values include incoming (13–70%) and outgoing heat reduction (3–80%) for living walls [80], and 14–43% for green facades [54]. The reason for this reduction is due to the absorptivity value of evergreen plants (0.4–0.6) to absorb and intercept solar radiation and the mitigating effect from the evapotranspiration process [21].

In addition, six articles have studied greenery systems with occupants [61,81–85] in office buildings. Mangone and van der Linden [81] applied a green canopy to cover the courtyard inside a building. They found that the green shading annually saved energy consumption by a maximum of 9.5% and varied according to the occupation load inside the building.

Moreover, Tseng et al. [61] measured the energy saving of an occupied building with a large vertical garden. The results showed that the vertical garden saved about 7–10% daily and 1.5% annually of the total energy consumption of the whole building. Also, Rodgers et al. [82] studied the effect of an indoor biowall in an occupied house on energy consumption. It was found that the power consumption was reduced by 27%. Poddar et al. [85] analyzed three types of buildings: a dormitory building, a research building, and an office building. The number of residents was only defined in a dormitory as 600 students. The power consumption was saved by 60%, 7% and 3% for a residential, research and administrative building, respectively. Dahanayake et al. [83] simulated an occupied office building with 4422 persons in China. The results indicate that the cooling load was saved by 34% in summer and up to 1.8% annual saving by applying the green wall system on external walls.

4. Discussions

The paper captured most articles from 2010 to early 2019 and presented a detailed analysis of the given information. It is found that the greenery systems can reduce external and internal surface temperature resulting in a reduction of the heat transfer from the walls and roofs. In the results section, the reduction values of heat transfer change according to the greenery classifications, the insulation effect, the climate effect. It is essential to discuss the reduction mechanisms, solar radiation concerning the diurnal, seasonal and special variation, the leaf area index, and the moisture content. The different findings from laboratory and field studies are also discussed. Also, the life cycle analysis is considered for each system in order to evaluate sustainability. Moreover, alternative methods are presented in order to save more energy consumptions. All of these were discussed below in separate items.

4.1. *Energy balance of greenery system*

The variation between the reduction values depends on the energy balance of the greenery systems, the plant characteristics, and the latent heat from the moisture content. First, the energy balance of any building envelope consists of three modes of heat transfer: radiation, convection, and conduction, as illustrated in Fig. 9. When the vegetated layer Ais added, it receives short wave radiation from the sun, and it also exchanges longwave thermal radiation between the ground, sky, and surrounding surfaces. The vegetation absorbs some of the incident radiation. Then, the heat flow through the vegetation is transferred by convection, if there is a layer of airspace, or transferred by conduction to the substrate layer then the bare wall. The energy balance of the vegetated wall also includes an additional term for the radiation exchange between leaves of the plant layer and the substrate surface for the living wall and green roof or the wall surface for the green façade.

Second, for the plant characteristics, many parameters are affecting the reduction of heat transfer through the wall or roof structure. These parameters include leaf absorptivity, which is the fraction of incident solar radiation absorbed by a leaf [95], leaf dimensions, which affect vapor conductance and convective heat between plant leaves, leaf area index which is defined as the total projected area of leaves per unit surface area. The parameters also include the radiation attenuation coefficient, which indicates the decrease in the absorbed radiation in the plant canopy. Besides, they include the leaf stomatal conductance, which is the rate of water vapor leaving the plant surfaces through the pores on the leaf surface during the transpiration.

Third, the latent heat is transferred through the moisture content, which comes from the amount of precipitation, according to the climate variation, the evapotranspiration process of the plants, and the water content in the substrate layer.

4.2. *Solar radiation*

The effect of incident solar radiation on the greenery systems have been diurnal, seasonally, and spatially studied. They have been discussed below.

4.2.1. Seasonal variation

A green roof was studied under various locations with different climates [96]. The cooling demand of a traditional roof in Tenerife, Spain of semi-arid climates is higher than Sevilla and Rome of temperate climates, and Amsterdam and Oslo of continental climates. Therefore adding a grass lawn on the roof with a drainage and substrate layer reduced the cooling demand by 7% in Tenerife, which was relatively higher than other climates with a range of 3%–6%, while the heating load was required more in continental climate than temperate climates, and almost negligible in an arid climate. The green roof achieved a higher reduction in heating load in Sevilla, which has a subtropical climate by 29% compared to others, which have a range of 6%–16%. In addition, a green façade was conducted on a laboratory study under various incident solar radiation in the summer season [54], when the solar radiation was zero at night and reached a maximum value of 800 W/m^2 during the day, the reduction in external surface temperature ranged from 0 to 13.9 °C and the corresponding reduction of heat transfer ranged from 0 W/m^2 to 35 W/m^2.

Moreover, the living wall was installed on the wall structure in modules by laying the turf on the substrate as studied in Ref. [57] in Hongkong of humid subtropical climate. The results revealed that the incident solar radiation was between 60 and 290 W/m^2 in the summer, the external surface temperature of using living wall reduced by 10 °C during the peak hour, and the substrate surface temperature was lower than the external surface temperature of a bare wall by 12 °C. Meanwhile, the heat flux of the living wall was an average of 7 W/m^2 compared to an average of 35 W/m^2 of the bare wall. That indicates that the maximum reduction of external wall temperature and wall heat flux achieved during the maximum incident solar radiation during the day and the season.

a) During the extreme cold weather

Some studies have conducted experimental work on the greenery systems during the extreme cold weather. For example, Bolton et al. [70] used ivy as a green façade on a building in Manchester, UK, where the average outdoor temperature was 10 °C. That protected the wall structure from temperature fluctuation since the ivy green façade increased the external surface temperature by 1.7 °C, which reduced the outgoing heat transfer of the wall by 8%. Also, Cameron et al. [65] studied the green façade covering all the walls of cuboids in Reading, Berkshire UK under extreme winter conditions where there was snow. The green façade helped to reduce the energy consumption by 20% to heat the inner space of studied cubes compared to the unplanted cubes. In contrast, Coma et al. [48] studied the green roof in the winter season. The incident solar radiation varied from 0 to 400 W/m^2, while the outdoor air temperature and relative humidity had an average of 7 °C and 90%, respectively. They found that the green roofs consumed more electric power, by an average of 10% than that of the reference roof due to the high thermal conductivity of the green roofs because of the stored water content in the soil. The most dominating parameter is the excess of moisture content, which adds more thermal conductivity, in the green roofs compared to other vertical greenery systems. This results in more energy consumptions by using green roofs, while others save energy consumption.

b) Diurnal variation

The diurnal change varies according to the studies location or climates and seasons. The diurnal range of direct solar radiation reaches the widest in winter and narrowest in summer, with average values for spring and autumn. For all seasons, the sunny day gets the most extensive diurnal range, with suppression on a cloudy day, and diminishing to almost zero on a rainy day. For instance, for the green roofs, Coma et al. [48] measured the interior roof surface in three cases without green roofs and with green roofs with different drainage layers in the temperature climate of Spain in the winter season. Both green roofs showed lower interior roof temperature compared to the reference roof in the cold weather. However, the electrical power consumption to heat the room was more in the green roofs compared to the reference roof. When the outdoor temperature varies from −0.1–13 °C, the interior surface temperature of the reference roof varied from 12 to 14 °C, while the green roofs varied from 10 to 12 °C. In the summer season, the cooling load of the green roofs was less than that of the reference roof. Similar trends in the studies of [96] have proven similar results in both a summer and a winter day.

For the diurnal variation effect on the green façade systems, Bolton et al. [70] explored the external surface temperature variation of applying the green façade to the building envelope in the winter season of Manchester, UK. The outdoor air temperature varied from 6 to 10 °C. The maximum and the minimum external surface temperature of a bare wall was 12 and 8 °C, respectively, while the maximum and the minimum external surface temperature of a vegetated wall was 10 and 9.8 °C at the same time day and night. At night the plant would reduce heat loss both by reducing the escaping the long wave of radiation from the external wall surface and protecting the wall from the wind, which reduces the convective heat loss. A similar trend was found in Ref. [65] study in the winter season where a room covered by green façade consumed about 20% less than that of the uncovered one.

For the living wall systems, Chen et al. [69] used a living wall system with an air space in China of subtropical climate during the summer season. The exterior and interior temperature of the living wall has a much smaller temperature fluctuation compared to the bare wall. During the daytime, the outside temperature of vegetated wall is much less than that of the bare wall at 20 °C, while at night, the bare wall was colder than the living wall by about 1 °C. The air layer was colder than the outdoor air by 10 °C, which results in saving energy consumption by 0.4 kWh less than that of the space without the greenery system. Another example, Olivieri et al. [53,81] explored diurnal variation in different seasons in Colmenar Viejo, Spain of hot-summer Mediterranean climate. The temperature of a bare wall during the day was higher than that of the living wall but less during night time in summer. During the spring and autumn season, the difference between the exterior surface temperature of the bare wall and the living wall during the daytime was 12 and 10 °C, respectively, and almost zero during the night time.

c) Spatial variation

Spatial variation refers to the orientation of the vertical greenery systems on the wall structure such as north, south, east, and west. Since the incident solar radiation on a vertical surface depends on the four directions, the effect of vertical greenery systems also depends on the directions of the walls. For example, Fernandez-bregon et al. [45] installed a living wall in Almeria, Spain, of the hot desert climate. Two living walls in north and south directions were compared with bare walls at the same directions. They found that the southern living wall was higher than the northern one by 2 °C, and both were less than that of the bare wall by 8 °C in the north and by 2 °C in the south direction. That is because the hourly global average solar radiation has been reduced by 32 W/m^2 in the south and 11 W/m^2 in the north.

Another example related to the green façade, Perez et al. [46] investigated the location of the green façade walls in different directions (in the northwest, southwest, and southeast facades) and measured the building wall surface temperature. They found that the green façade temperature of the southeast façade was the highest with an average of 32 °C while the northwest façade was the lowest of 28 °C, and both of them were lower than that the wall without plants having an average of 40 °C. Similar to Jim and He [97] where the south living wall was higher than the north living wall, and both of them were lower the bare wall. The south bare-wall gets the highest value of hourly global solar radiation in summer (1170 W/m^2), followed by north bare-wall (1030 W/m^2), while the south and the north green wall received solar radiation of 890 and 730 W/m^2, respectively.

4.2.2. Leaf area index

The leaf index describes the density of the plant layer covering the wall surface and affects the reduction of the external surface temperature and heat flux reduction. Different leaf area index was investigated under the same relative humidity and incident solar radiation. For instance, Susorova et al. [54] used different leaf index values ranged from 0 to 4 to evaluate the thermal performance of a green façade. The results showed that the reduction in the external surface temperature varied between 0.8 and 13.1 °C, while the heat flux reduction ranged from 2 to 33 W/m^2. The zero leaf index means that there is no leaf coverage on the surface, but there was a plant stem sticking to the wall which added a small amount of thermal resistance and helped in a slight heat reduction. Also, Sailor [98] found that the higher leaf area of 5 increased gas consumption in the winter and reduced electricity consumption in the summer.

Similarly, Carlos [79] investigated the living wall under variable leaf area index in winter; he found that decreasing the leaf area index (from 5 to 0.5) will increase the reduction of the heating load by 1%. The reason for that, the plant layer functions as a solar barrier reducing the absorption of solar energy throughout the day. A lower solar reflection and also higher solar absorptance of the soil allow the useful solar heat to increase the outer surface temperature.

4.3. Moisture content

The moisture content is another factor, which comes from three main items: the evapotranspiration process of plants, the amount of precipitation, and the irrigation process. The majority of studies have linked the reason for the moisture content to the precipitation or the relative humidity of the ambient air since the amount of moisture from evapotranspiration process is very small compared to the amount of precipitation. When the ambient relative humidity is low, plants significantly decrease the rate of evaporation as a way to protect themselves from dehydration [99]. When the relative humidity is high, the rate of evaporation from plants significantly increases. This process is controlled by stomatal pores on the plant surface, which open and close depending on surrounding humidity. For the green roofs, Alexandri and Jones [100] observed the evaporative heat fluxes from the concrete roof of a range from -46.3–170.6 W/m^2 and from a green roof of a range of -593.2 to -26.4 W/m^2.

For the green façade systems, Different relative humidities were investigated under the same incident solar radiation [54]. The range of the outdoor relative humidity was from 20 to 100% the reduction of external surface temperature varied between 11.9 and 14.2 °C and the heat flux reduction changed from 30 to 36 W/m^2. The construction of the green façade is to cover the wall with climbing plants directly without a substrate layer since it is on the ground. The heat reduction refers to the radiation and convective heat transfer, while the latent heat is almost negligible since plant leaves absorb a small amount of vapor water because of the saturation of air (100% relative humidity). In the case of freezing weather, the use of green facades helped to keep the wall dry during rainfall periods [65]. Plant leaves intercepted and deflected precipitation away from the wall. However, they caused increasing energy consumption in winter to warm the selected place.

The living wall systems consist of an additional substrate and support layers to the vegetation layer. The substrate layer acts as a moisture sink, which adds more thermal resistance to the wall. Reducing the saturation volumetric moisture content of the soil increased the reduction of heating load by about 7% [79]. However, during the raining day and in winter, the thermal resistance of the wet soil increased as adding another layer of insulation. The overall thermal conductivity of the dry soil and the wet soils were 1.7 and 1.2 W/m^2.K, respectively. Therefore, the wet soil was able to reduce the heating load more compared to the dry soil.

An additional layer of air space behind the living walls help in lowering the relative humidity in the air space and consequently in the indoor place. For example, Chen et al. [69] investigated the relative humidity in different air spacing. They found that the average relative humidity of the sealed air layer is 88.2%, much higher than the open-air layer (74.7%) and the ambient air (75.6%). The air space layer provides natural ventilation to lower the relative humidity.

4.4. Laboratory and field studies

The majority of studies have conducted laboratory studies that showed a significant impact of plants on the reduction of external surface temperature as well as heat transfer through the walls and roofs. Few investigations have performed in a field study; six studies have conducted in 2017 [51,66,84,86,88], one in 2016 [53], three in 2014 [44,68,81], two in 2013 [54,61], and one study in 2011 [94], as shown in Table 2. Few of them are investigating the greenery system in an occupied building, or the number of residents is not mentioned. Cuce [86] have investigated the green façade on the Jubilee Campus of the University of Nottingham in the UK. There is no information regarding the number of students on the campus. The heat transfer was reduced by 43% due to external and internal surface temperature by 4–6 °C and 2.5 °C, respectively. Besides, Tseng et al. [61] measured the energy consumption of a real, occupied, office-building in Taiwan of humid subtropical climate. A large size living wall was covered a whole west side of the building.

The results showed that the vertical garden saved energy consumption of the building with an average of 8% daily, and external surface temperature reduction was 2.2 °C in summer. However, energy saving in winter was minimal. The total saving of energy consumption was 1.5% annually. Moreover, Mangone and van der Linden [81] measured the energy consumption of using a green shading for a courtyard inside an office building in Ghana, which has a tropical savanna climate. The green shading was able to reduce the temperature of the courtyard by an average of 1.1 °C during the day and a maximum of 2.0 °C on the peak summer day. It also reduced the peak cooling loads of the air-conditioned spaces that are adjacent to the courtyard by an average 21.3%, which was less than that of a metal shading by 2.3%. When 5% of building occupants occupy the courtyard, the cooling load is reduced by an additional 0.5%. Using a large surface area of greenery systems on the wall structure has a relative effect on energy saving in real buildings.

4.5. The life cycle analysis

This review paper focuses on the findings from laboratory and field experiments, so any study related to the life cycle analysis was not captured, but it is briefly discussed to assess the sustainability of using the greenery systems. For the roof, the life cycle cost was performed by Ref. [101]. The life cycle costs consist of structural cost, which is the cost of constructing roof decks with and without roof gardens, initial costs, maintenance, and replacement costs. They found that the initial cost of extensive green roof systems was substantially higher than that of a reference roof due to the excess material of a substrate, drainage, and plants, and it varies according to the selection of planting and a type of structure. However, the life-cycle cost can be reduced by adding the benefits from energy savings from the green roof system.

In addition, Feng and Hewage [38] established a comparison of the life cycle analysis between the green façade and two types of living walls: those using felt layer and planter box systems. The life cycle analysis includes the initial cost, manufacturing and construction cost, and maintenance cost. They found that the green façade system is more economical and environmentally sustainable system than other systems similar to [39,40].

Moreover, Ottelé et al. [102] found that the living wall system based on felt layers used twice the amount of watering rather than planter-boxes living wall and much more than green facades, its waste cannot be recyclable, and it was necessary to replace the panels five times in a service life of 50 years. It also has a high environmental burden due to the durability aspect and the materials used. However, the green façade has a minimal influence on the total environmental burden, and without any additional material involved. The sustainability of a system depends on the difference of the environmental benefits (such as energy savings) and burdens (using additional materials, manufacturing, maintenance, and recycling). It was found that the green façade without using trellis on the walls to support climbing plants can always be a sustainable choice since it has less environmental burden compared to other greenery systems. A similar trend was also found in the study of [103].

4.6. Alternative methods

Comparing other alternative ways to save energy, Floride et al. [104] presented different insulations and their effect on cooling and heating load in a full-scale house with four external walls and a window on each wall. The cooling load of the house substantially decreased by 42.9 and 51.5%, and heating load decreased by 59.3 and 66.5% for 25 mm roof insulation only and 50 mm roof and all walls insulation, respectively. Similarly, Al-Sanea [105] investigated different types of roof insulations with different insulation materials. Using a lightweight of foam concrete type, reduced the heat transfer load by 45%, while the heat transfer load decreased by an average of 27% by using 5-cm thick insulation materials. Adding artificial insulation materials into walls and roofs showed a more significant impact on energy saving (heating and cooling loads) compared to the greenery systems discussed above.

5. Conclusion

Plants have been used as external insulation to the buildings in order to reduce building energy consumption. The purpose of this review paper is to analyze the effect of plants on the energy use of buildings based on previous research from 2010 to early 2019. Fifty-six articles are studying the effect of greenery systems on building energy consumption.

The main results obtained from this review are that the greenery systems can be used as insulation, block solar radiation, and reduce the wall and roof surface temperature resulting in a reduction in heat transfer through building envelopes, which can be as high as 80–90%. The greenery systems have a significant impact on hot and dry climates since they were able to block high solar radiation and produce the cooling effect from the evapotranspiration process. Excessive amounts of moisture content due to precipitation can increase the heat transfer load since they add unwanted latent load needed to be removed. Plants also have a significant effect during the daytime more than in night time and summer more than in winter seasons. More foliage coverage on the wall or roof structure can have a more significant effect of external temperature reduction than no or limited coverage — this yields to save building energy consumption.

The captured articles have focused their measurements on external surface temperature and ambient air temperature for comparison, and few studies have considered the interior surface temperature and indoor conditions such as indoor temperature and indoor relative humidity. The lack of the existing studies is concentrated in the field investigation of greenery systems in occupied spaces in different climate conditions to address the actual effect of greenery system.

Some future recommendations should be considered based on this review. All measured parameters for indoor and outdoor should be undertaken in the research. This step is vital for assessing the sensible and latent heat transfer of greenery systems. Also, investigating the greenery systems should be considered in an occupied building for different human activities. Moreover, a comparison should be established among different building envelope systems such as Trombe walls, solar walls, and vegetated walls to help decision-makers for selecting the proper wall for saving building energy.

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