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Thermal aspects of living walls: a review on the influence of different structural materials and plant species

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SUMMARY

The use of living walls, a type of vertical garden, promotes the reduction of surface temperatures in buildings, and the choice of the appropriate plant species can contribute to optimizing the passive cooling of buildings. To better understand this issue, this study aimed to evaluate the thermal performance of living walls. For this purpose, a systematic review was conducted in the Scopus database using the keywords 'green wall, living wall, vertical garden, and 'thermal performance' present in the titles of articles, in the time frame from 2011 to 2021, and in the fields of architecture and urbanism; engineering; environmental science; agriculture; and biological sciences. Sixty-seven articles were identified, and after screening for articles relevant to the topic, 29 were selected. The analysis of the results showed that the layers, the type of material (PVC and felt), and the species used influence the system's performance. Regarding the species, only 11 articles identified the names, and only 4 evaluated the thermal performance of each one. The PVC-type structure proved to be more efficient, with a longer lifespan and durability of vegetation, as it provides a larger area for root development.

KEYWORDS: Vertical garden. Living wall system Thermal efficiency.

1 INTRODUCTION

Due to the adverse effects caused by urbanization on urban microclimates, which contribute to the formation of heat islands, the combined use of different types of green infrastructure, such as urban tree planting, green roofs, and vertical gardens, among others, can help alleviate this issue. By shading walls and pavements, vegetation promotes the reduction of surface temperatures, contributes to increased humidity through evapotranspiration, and, consequently, facilitates the reduction of heat flow into the interior of buildings.

Due to the decrease in available gardening space, the use of living walls on buildings has been increasingly practiced. The living wall is a type of vertical garden (CHAROENKIT; YIEMWATTANA, 2021) that, in addition to serving an aesthetic function, can promote thermal and social well-being in indoor and outdoor environments.

Several authors have been devoted to understanding the thermal effects of living walls, including Razzaghmanesh and Razzaghmanesh (2017), Reséndiz et al. (2018), Chen et al. (2019), Nan et al. (2019), Charoenkit et al. (2020), Shafiee et al. (2020), Yuan et al. (2020), and Gräf et al. (2021). Among these authors, Yuan et al. (2020) and Gräf et al. (2021) emphasized the effect of vegetation on the thermal performance of the living wall system.

In this context, this article analyses by a literature review how different material of the structure (PVC and felt) and plant species influence the thermal performance of the living wall system (comprised of the structure, substrate, and plant species).

2 OBJECTIVE

Analyze if different material of the structure (PVC and felt) and plant species influence the thermal performance of the living wall system. .

3 METHODOLOGY

To response if different material of the structure (PVC and felt) and plant species influence the thermal performance of the living wall system, this research used the literature review. For this, the research process was defined in 3 phases: 1. selection of the database to be explored and definition of keywords for conducting the search; 2. definition of eligibility criteria for scientific articles; and 3. parameters for analyzing the articles.

The chosen database was Scopus, as it contains high-impact journals. Using the English keywords 'green wall, living wall, vertical garden,' and 'thermal performance' present in the title, within the period from 2011 to 2021, in the following areas of interest: architecture and urbanism; engineering; environmental science; agriculture; biological sciences; and energy. With these filters, 67 academic articles were selected.

The inclusion criteria involved articles that assessed the thermal performance aspects of living walls through measurements in buildings. For exclusion criteria, studies on simulation, green facades, and green roofs, among others, were not considered. After the selection of the 67 academic articles, eligibility criteria were applied, such as 1- reading the titles, abstracts, and keywords; 2-the subject of the article; and 3- the availability of the complete article for reading. With the application of these criteria, the number of articles was reduced from 67 to 29 studies.

The selected articles were Franco et al. (2012); Mazzali et al. (2012); Chen, Li, and Liu. (2013); Mazzali et al. (2013); Perini et al. (2013); Feng and Hewage (2014); Jorgensen et al. (2014); Martensson et al. (2014); Perini and Ottelé (2014); Pulselli et al. (2014); Scarpa et al. (2014); Charoenkit and Yiemwattana (2017); Jorgensen et al. (2017); Razzaghmanesh and Razzaghmanesh (2017); Safikhani and Baharvand (2017); Tudiwer and Korjenic (2017); Reséndiz et al. (2018); Chen et al. (2019); Cosola et al. (2019); De Masi et al. (2019); Nan et al. (2019); Tudiwer et al. (2019); Charoenkit et al. (2020); He et al. (2020); Mannan and Al-Ghamdi (2020); Shafiee et al. (2020); Yuan et al. (2020); Charoenkit and Yiemwattana (2021); and Gräf et al. (2021).

The analysis of these articles involved parameters related to general characterization (author data, year of publication, type of living wall structure, geographical orientation of the living wall, climate of the location) and characterization of the structure used, vegetation and analysis techniques (installation of temperature sensors).

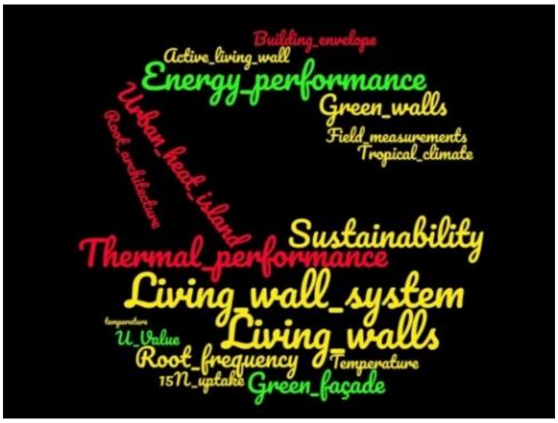
4 RESULTS AND DISCUSSIONS

The presentation of the results begins with an initial characterization of the research (keywords, countries, universities, journals), followed by data on the structures used, plant species, and methods and techniques for analyzing their influence on thermal attenuation of living wall systems.

4.1 General characterization

Figure 1 shows the word cloud collected found out in the 29 papers analysed. The words that stand out the most are living walls, living wall systems (structures), thermal performance, and energy performance. However, it is important to note that none of the articles were keywords related to the thermal performance of the plant species used. The only mentions related to plants are about root system architecture and root frequency.

Figure 1 - Word cloud



Source: Adapted of WordCloud (2003).

Table 1 presents the scientific journals where the 29 articles were published: Sixteen in the journals 'Energy and Buildings' and 'Building and Environment,' which accounts for approximately 55% of the total. All other journals presented only one article with the respective theme.

Table 1 - Number of articles published in journals and their respective Qualis (CAPES)

Number of articles	Qualis Capes	Journal
11	A1	Energy and Buildings
5	A1	Building and Environment
1	A1	Eco-Architecture; Ecological Engineering; Energy Conversion and Management; Energy Reports; Int. J. of Design & Nature and Ecodynamics; Journal of Cleaner Production; Journal of Environmental Management; Landscape and Ecological Engineering; Plant Soil; Sensors; Sustainability; Urban Ecosyst e Urban Forestry & Urban Greening

CAPES - Coordenação de Aperfeiçoamento de Pessoal de Nível Superior.
Source: The authors, 2022.

Table 2 shows that 15 institutions each published only one article. However, 20.6% of the publications are concentrated at the University of Venice in Italy and Naresuan University in Thailand, with three articles from each institution. Nevertheless, the low quantity of publications generated by each institution demonstrates that the subject is still relatively underexplored.

Table 2 - Distribution of publications by teaching and/or research institutions

Number of articles	Teaching and/or research institution	Country
3	IUAV - Venice University	Italy
3	Naresuan University	Thailand
2	Vienna University of Technology	Austria
2	Huazhong University of Science and Technology	China
2	Madrid Polytechnic University	Spain
2	Genova University	Italy
1	University of South Australia	Australia
1	University of Natural Resources and Life Sciences	Austria
1	University of British Columbia	Canada

Number of articles	Teaching and/or research institution	Country
1	Hamad Bin Khalifa University	Qatar
1	School of Landscape and Architecture	China
1	South China Technology University	China
1	Copenhagen University	Denmark
1	Danish Technological Institute	Denmark
1	Seville University	Spain
1	University of Tennessee	States United
1	Islamic Azad University	Iran
1	University of Science and Technology	Iran
1	University of Sannio	Italy
1	Siena University	Italy
1	Swedish University of Agricultural Sciences	Sweden

Source: The authors, 2022.

4.2 Structure, vegetation, and analysis methods and techniques

The structures of living walls used in the selected research on living wall performance are listed in table 3. It can be observed that structures composed of felt were used in 44.8% of scientific research, PVC and felt (24.10%), PVC module (17.2%), PU foam (6.9%), and those with less usage were composed of rock wool and concrete modules (3.5% each).

Table 3 - **Living wall structure used in selected articles**

Living Wall Structure	Number of articles	Authors
Felt	13	Franco et al. (2012); Mazzali et al. (2012); Chen, Li e Liu (2013); Jorgensen et al. (2014); Scarpa et al. (2014); Pulselli et al. (2014); Jorgensen et al. (2017); Tudiwer; Korjenic (2017); Chen et al. (2019); Nan et al. (2019); Tudiwer et al. (2019); Mannan; al-Ghamdi, (2020); Yuan et al. (2020) e Gräf et al. (2021)
PVC e Felt	7	Mazzali et al. (2013); Perini et al. (2013); Feng; Hewage (2014); Perini; Ottelé (2014); Cosola et al. (2019); Charoenkit et al. (2020) e Charoenkit e Yiemwattana (2021)
PVC module	5	Charoenkit; Yiemwattana (2017); Razzaghmanesh; Razzaghmanesh (2017) e Shafiee et al. (2020)
PU foam (PU)	2	He et al., 2017; De Masi et al., 2019
rock wool	11	Martensson et al. (2014)
concrete modules	11	He et al. (2020)

Source: The authors, 2022

Regarding the use of PVC in the structure of living walls, some authors (CHAROENKIT; YIEMWATTANA, 2017; RAZZAGHMANESH; RAZZAGHMANESH, 2017; SHAFIEE et al., 2020) mention that this material is easier to apply, reduces implementation costs, provides a larger substrate volume, and consequently, a larger root exploration area, lower maintenance costs, and a longer lifespan for the structure. According to these authors, felt has a lifespan of 10 years, while PVC has a lifespan of 20 years.

All authors were consistent in highlighting the thermal efficiency of living walls, mentioning that the use of this technique promotes passive cooling of the studied surfaces and the indoor environment. However, the types of structures showed significant differences in terms of the rate of heat transfer from the external surface to the indoor environment.

Charoenkit and Yiemwattana (2021) observed a reduction of 2.4°C in the indoor environment with the use of PVC modules. When comparing the use of felt with PVC modules, Charoenkit and Yiemwattana (2021) noted that the modules contributed to a temperature reduction of 3°C compared to the felt structure.

The studies that evaluate felt living walls compared to PVC module walls describe that felt is expected to lose market share rapidly in the coming years because PVC module living walls require less maintenance, and the plants have twice the lifespan. In other words, plants in felt live for about 5 years, while in modules, they live for 10 years.

Table 4 quantifies the number of articles based on the geographical orientation of the studied living walls because this is a fundamental factor, considering that the orientation indicates whether the structure is receiving the maximum solar radiation during the day and, consequently, a higher heat gain.

Approximately 63% of the articles did not describe the geographical positioning of the studied living wall, indicating a methodological flaw during the preparation of the scientific article. It is worth noting that for locations in the northern hemisphere, the geographical orientation with the highest receipt of solar radiation is the south, while in the southern hemisphere, the most favorable orientation for receiving sunlight is the north. Only Chen et al. (2019) analyzed all four geographical orientations to assess the differences in the thermal potential of living walls in different positions.

Table 4 - Geographical orientation of the living walls studied

Geographic orientation	Number of articles	Percentage
Uninformed	19	63.3
West	4	13.3
South	3	10.0
South-west	2	6.7
South-west and East	1	3.3
North, South, East and West	1	3.3

Source: The authors, 2022

However, what is most noteworthy are the studies conducted by Chen, Li, and Liu (2013) in China, Razzaghmanesh and Razzaghmanesh (2017) in Australia, Charoenkit et al. (2020), and Charoenkit and Yiemwattana (2021), both in Thailand, with walls facing the west.

Table 5 presents the climates of the research development locations. It can be observed that 65.6% of the articles did not provide information about the climate of the region. On average, 17% of the studies were conducted in a Mediterranean climate (hot and dry), 13.7% in a humid tropical climate (hot and humid), and 3.4% were carried out in a humid continental climate (hot summer and severe winter with temperatures below -3°C).

The same pattern was observed regarding the season of thermal assessment was carried out since that 66.7% of the articles do not mention it; 16.7% were conducted in the summer, the hottest time of the year when the walls receive the most sunlight; 13.3% conducted studies in both summer and winter, evaluating the potential of living walls to serve as thermal insulation in winter, potentially delaying the cooling of the indoor environment, and 3.3% were conducted in spring, summer, and autumn.

Table 5 - Climate of the location where the research was carried out

Climate	Number of articles
Uninformed	19
Mediterranean	5
Humid tropical	4
Humid continental	1

Source: The authors, 2022.

All the analyzed articles describe the importance of measuring temperature on a control surface, i.e., without the influence of the living wall, on the surface of the living wall itself, and on both surfaces of the wall that serve as support for the living wall (external and internal faces). The authors unanimously describe that temperature and humidity measurement sensors should always be installed in the center of the living wall, regardless of the structure, to avoid the influence of the edges.

Practically all studies used K-type thermocouple temperature sensors with an accuracy of 1°C installed at different points. Only the study conducted by Razzaghmanesh and Rrazzaghmanesh (2017) used button sensors. The differentiates most of the articles is the location of temperature sensors, as all authors measured the temperature of the external environment, the surface of the wall, the internal surface of the wall, and the indoor environment.

In Table 6, you can observe the location of temperature sensor installation on living walls. In 65.5% of the articles, the experiments only used temperature sensors installed in the external environment of the living wall and in the indoor environment.

Table 6 - Installation location of temperature sensors on the living wall

Temperature sensors installation location	Number of installation *
1 m from the plant surface	1
0.1 m from the plant surface	1
0.3 m from the plant surface	1
Plant surface	7
External surface of the module	3
Substrate	1
External surface of the wall	5
Inner wall surface	2
Internal environment	29
External environment	29

* A single article may have sensors installed in more than one location.

Source: The authors, 2022.

A more comprehensive study would be one that evaluates the thermal performance of all components between the external and internal environments. The study that came closest to this goal was that of Charoenkit and Yiemwattana (2017) because the authors, in addition to assessing the influence of the substrate, also studied all surfaces independently.

The measurement of temperature on the surface of plants was conducted by Chen, Li, and Liu (2013), Charoenkit and Yiemwattana (2017), He et al. (2017), Razzaghmanesh and Razzaghmanesh (2017), Chen et al. (2019), Charoenkit et al. (2020), and Charoenkit and Yiemwattana (2021). According to the authors, the purpose of assessing temperature on the surface of plants and in their proximity is that they undergo photosynthesis, and consequently, the gas exchange due to transpiration releases humidity into the environment, which can contribute to lowering air temperature and improving thermal comfort conditions.

Only He et al. (2017), Chen et al. (2019) and Charoenkit and Yiemwattana (2021) conducted an analysis of the temperature on the external surface of the modules. This measurement allows for the determination of the thermal performance of the plant species by subtracting the temperature of the external environment from the temperature of the external surface of the module, resulting in the thermal performance of the species.

Measurements of temperatures between the modules and the external surface of the wall were made in five studies (MAZZALI et al., 2012; MAZZALI et al., 2013; HE et al., 2017; RAZZAGHMANESH; RAZZAGHMANESH, 2017; CHAROENKIT; YIEMWATTANA, 2021). This measurement determines the influence of the physical support structure on the heat transfer rate. All studies measured the surface temperature of the internal environment and a control on the structural wall under study, without the living wall infrastructure for the purpose of comparing results. The wall without plants tends to transmit more heat flow and consequently raise the temperatures of its surfaces and the ambient temperature internal.

Regarding the frequency of data collection, only 20% of the studies reported the data collection frequency and described the use of dataloggers for automated data capture. He et al. (2017) collected data every 5 minutes, Charoenkit and Yiemwattana (2017) and Charoenkit et al. (2020) every 10 minutes, Charoenkit and Yiemwattana (2021) and Chen, Li, and Liu (2013) every 30 minutes, and Chen et al. (2019) every 2 hours. The remaining articles did not describe the data collection frequency.

The authors emphasize the importance of knowledge about the plant species to be used in a living wall because each species has a different cooling capacity. However, designing a living wall system for passive cooling is a complex task. Designers must understand the thermal resistance of the materials used in the wall, the structure of the living wall, the substrate, and the plants. Additionally, geographic data and solar radiation data are essential for the design process.

Out of the 29 articles, only 11 of them (38%) described the plant species used in the living walls. Among these, only 4 (14% of the total) evaluated the individual thermal performance of the plant species. In total, the eleven articles described 65 plant species used, but they individually evaluated only 15 species (Table 7). It's noteworthy that only 19 species (29.2%) were used in more than one study.

Ninety-seven percent of the plant species described in the articles have a perennial life cycle (indefinite lifespan), while only 3% have an annual cycle (*Goodenia pinnatifida* and *Tibouchina urvilleana*), which need to be replaced annually.

Table 7 - Plant species grown in live walls

Frequency of use	Scientific name
3	*Cuphea hyssopifolia Humb; Fragaria vesca cv. 'Smålan; Sesleria heuffleriana*
2	*Aerva sanguinolenta (L.) Blume; Alternanthera bettzickiana (Regel; Alternanthera sp.; Asystasia gangetica (L.) T. Anderson; Bergenia cordifolia; Campanula poscharskyana; Convolvulus sabatius Viv; Cynodon dactylon X Cynodon trasvalensis 'Patriot'; Geranium sanguineum cv. 'Max Frei'; Ligustrum sinense Lour. Cv Variegatum; Melampodium divaricatum (Rich.) DC; Portulaca grandiflora Hook; Portulaca oleracea L.; Salvia nemorosa; Tradescanti-a spathacea Sw; Veronica officinalis cv. 'Allgrün*
1	*Achillea millefolia; Alchemilla mollis; Anemone sp.; Antennaria dioica; Armeria maritima; Atriplex semibaccata (Berry Saltbush); Aubretia × cultorum; Brachyscome ciliaris (Variable Daisy); Carex morrowii; Dianthus deltoides; Dicondra; Enneapogon nigricans (Black Heads); Excoecaria cochinchinensis; Geranium Johnson's blue; Geranium sanguineum; Goodenia pinnatifida; Hardenbergia violacas; Heuchera micrantha Palace Purple; Iberis sempervirens; Iris sibirica; Ixiolaena leptolepis; Juniperus communis Sedum spurium; Kennedia prostrata; Lonicera pileata; Molinia caerulea; Nepeta faassenii; Oenothera missouriensis; Parthenocissus tricuspidata; Paspalum vaginatum; Pilosella aurantiaca; Pittosporum tobira; Plumbago capensis; Poa labillardieri (Tussock Grass); Pteropsida; Ptilotus nobilis; Rosmarinus de fi cinalis; Sansevieria trifasciata hort ex Prain cv. Golden Hahnii; Schefflera octophylla (Lour.) Harms; Stachys byzantina; Stenotaphrum secondatum; Tibouchina urvilleana; Vinca Variegata; Zoysia; Zoysia japonica 'El Toro; Zoysia matrella 'Zeon; Zoysia tenuifolia*

Source: The authors, 2022.

In Table 8 presents the leaf size of plants cultivated on living walls. 47 species (72%) have small-sized leaves, while 14 species (approximately 22%) have plants with smaller leaves tend to have a greater number of branches and, therefore, more leaves, which results in more layers of protection against solar radiation.

Table 8 - Leaf size of plant species grown in live walls

Number of species	Leaf size
47	Small
14	Medium
4	Large

Source: The authors, 2022.

According to Table 9, 80% of plant species, which is 52 species, have a ground-cover growth habit, with more horizontal growth than vertical, giving them a trailing characteristic in living walls, accelerating the process of wall coverage on building facades.

Table 9 - Growth habits of plant species grown in live walls

Number of species	Growth Habit
2	Climbing shrub
2	Herbaceous climber
9	Shrub
52	Forage

Source: The authors, 2022.

Nine species (14%) are slow-growing, erect shrubs ranging from 0.5m to 2.5m in height, with a taproot system that can cause structural damage. 6% of the species are climbers, evenly divided between shrubby and herbaceous types. The main characteristic here is the stem composition, with herbaceous climbers having more than 90% of their composition as water, with fragile branches, while woody climbers are rich in carbon, rigid, and resistant to wind.

In landscape designer reports, it is common to note a limited availability of ornamental plants for full sun cultivation. However, as shown in Table 10, 62 species are suitable for full sun cultivation, 39 species can be grown in partial shade, and only 8 can be cultivated in shade. This indicates greater difficulty in selecting plant species for installing living walls in indoor building environments.

Table 10 - Cultivation luminosity of plant species grown in living walls

Number of species	Cultivation luminosity
1	Half shade and shade
2	Half shade
7	Full sun, partial shade and shade
26	Full sun
29	Sun or partial shade

Source: The authors, 2022.

Table 11 shows the results obtained of the thermal performance for each plant species analyzed individually.

Table 11 - Thermal performance of plant species grown in live walls

Scientific name	Structure		Thermal amplitude (°C)	Percentage (%)
	Felt	PVC module		
	Temperature (°C)			
Cuphea hyssopifolia Humb	8.6	26.7	-1.9	6.6
Alternanthera bettzickiana(Regel)	9.9	27.9	-2.0	6.7
Portulaca oleracea L	7.3	27.4	0.1	0.4
Portulaca grandiflora Hook	0.3	27.5	-2.8	9.2
Aerva sanguinolenta (L.) Blume	7.8	27.8	0.0	0.0
Asystasia gangetica (L.) T. Anderson	7.7	27.5	-0.2	0.7
Convolvulus sabatius Viv	7.5	27.5	0.0	0.0
Ligustrum sinense Lour. Cv Variegatum	9.9	27.9	-2.0	6.7
Alternanthera sp.	7.9	27.4	-0.5	1.8
Melampodium divaricatum (Rich.) DC	8.1	27.2	-0.9	3.2
Sansevieria trifasciata hort ex Prain cv. Golden Hahnii	9.6	28.0	-1.6	5.4
Tradescantia spathacea Sw	8.2	27.6	-0.6	2.1

Source: The authors, 2022

It can be observed that the type of structure influenced the response of plant species regarding passive cooling of the building surface. This can be explained by the fact that PVC modules provide larger volumes of substrate for root exploration compared to felt. In felt structures, the substrate pockets contain only 100 ml of growing medium, whereas PVC modules have 12 liters of substrate, a volume 120 times larger than felt structures.

The articles also demonstrate that plant species behaved differently from each other, highlighting the importance of understanding the thermal performance of each species. The highest temperature observed was on the surface with Alternanthera bettzickiana (Regel) cultivation, with a temperature of 27.9°C, while the lowest was observed with Cuphea hyssopifolia Humb cultivation, with a temperature of 26.7°C, a difference of 3.2°C. This variation in temperature between different plant species emphasizes the need for careful selection when designing living walls for thermal performance. Different thermal amplitudes were observed among the cultivation structures of the species *Cuphea hyssopifolia* Humb due to the materials composing the living wall structure, reaching a 2°C amplitude.

5 CONCLUSION

The results obtained from the review of the literature on the influence of plant species on the thermal attenuation of living wall systems, as well as systems used, have demonstrated the importance of knowledge of the components of the living wall structure since it directly influences the thermal performance of the living wall system. The plant species provide different thermal performances; that is, each species has its own influence on thermal transmissibility, whether with the elevation or reduction of the surface temperature of the building, demonstrating that it is possible to maximize the passive cooling of buildings.

Many articles presented shortcomings in the characterization of information on the experiments such as: 1. do not mention the periodicity of data collection; 2. did not report the geographical positioning in which the living wall was being studied (more than half of the articles); 3. most articles installed temperature sensors only on the external surface of the live wall and on the inside of the building, not being able to analyze all the components (layers) between the surfaces as plant species, type cultivation substrate, living wall structure and structure of the edifice wall; 4. part of articles evaluated the thermal performance of species grown randomly, failing to attribute the good thermal performances observed for specific species. This latter observation makes clear the field of research to be explored, for greater knowledge of the specific contribution of vegetation to the thermal performance of the living wall system.

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