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Methods, Area Ratio and Plants of Biowall to Induce Atmospheric Comfort: A Review

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Abstract

Biowall is one of the several innovative strategies people use to build a comfortable interior atmosphere with living plants. This research attempts to trace the gaps in the previous analysis as a 'state of the art' with a literature review method by focusing on the biowall method, area ratio and types of plants. Biowall performance is mainly related to the influence of thermal, visual, audial, and respiratory comfort. It is an essential topic used to induce atmospheric interiors, such as temperature, humidity, light intensity, sound insulation and absorption, CO_2, HCHO, VOC, and particulate levels. The results showed that the empirical methods used were actual scale-up and down experiments, laboratories in test chambers, simulation with specific software, and case research on in-situ biowall. The comparison between the biowall and room size varied significantly due to the absence of a legal basis and reasons. Ferns and succulents were the most widely used species to induce atmospheric comfort. Therefore, it is necessary to conduct further research on biowall physical comfort based on multisensory simultaneously and determine its standard dimension and digital integration. Subsequent researchers must further discuss home-scale biowall acceleration and utilization of food-medicinal plants.

Keywords: biowall; area ratio; comfort; method; plant.

Introduction

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Before the 1950s, research topics were related to biowall in botanical matters and its implementation in objects. From 1950 to 2000, the ecological system emerged with the use of plants reputed as a manifestation of human efforts to repair expected ideal conditions. On the other side, science development emphasizes the need for a holistic mindset. The fundamental topic of a botanical, planning and ecology process started to develop with the addition of cross-discipline issues, such as technology, psychology, energy, biodiversity, food, and physical human comfort. Others have also started to evaluate this process as a plectic architecture (Andadari, 2021).

This research found some biowall nomenclature from the reference, which covers a living wall, facade greening, green curtains, green façades, greenery façade, living green wall, vertical farming, vertical green façade, vertical green walls, vertical greenery modular system, vertical greenery systems, vertical greening and vertical greening façade. Biowall terminology is destined explicitly for vertical vegetation in interior areas (Andadari et al., 2023), and its definition is identical to exterior vertical greening placed in an indoor room (Stav, 2016). Furthermore, biowall terminology in this paper emphasizes that this review discusses its relation to interior atmospheric comfort.

Vertical greening has two categories: green wall and living wall systems. A green wall is a term for plants that grow and cover the wall surface directly or through other structures (Palermo & Turco, 2020). In contrast, the living wall system is more broadly related to technology, vegetation, plant growth, irrigation, and nutrition systems (Giordano et al., 2017). It can be in the form of pre-vegetated panels and vertical modules on the wall. The continuous, modular (Gunawardena & Steemers, 2019), and linear biowalls (Medl, Stangl, & Florineth, 2017) are the various types commonly applied in interiors. Continuous biowall uses a double steel net construction filled with compost and rocks as a planting medium (Medl, Stangl, Kikuta, et al., 2017). Modular biowall consists of a planting bag holding organic or inorganic growing media, such as foam, mineral wool, felt, and perlite. Meanwhile, linear biowall consists of one box horizontal plant from HDPE plastics, aluminum, or woods filled with the substrate.

However, biowall consists of four available systems, namely the trellis, planting container, felt, and planting pot systems (Tamási & Dobszay, 2016). Trellis systems use support structures to propagate plants directly on the soil surface and container box below the building. Planting container systems do not have direct soil contact and select non-vines vegetation. The felt system uses geotextile material, hence it is flexible and can adjust to the textured surface. The planting pot system has an iron frame hanging by plant pots.

The interior atmosphere significantly impacts resident satisfaction, health, and productivity, with a direct relationship to human comfort. The role of biowall is associated with interior atmospheric conditions that can stimulate humans to respond with their senses. These conditions consists of four aspects, namely thermal, visual, audial, and respiratory (Song et al., 2019). It is essential to condition the atmospheric quality of this space because people spend more of their time indoors.

Connecting the biowall to interior comfort is motivated by its positive results in influencing temperature, humidity, light intensity, sound absorption, particulate, CO_2, formaldehyde, and VOC levels. Conversely, preliminary reviews discussed the performance of the biowall partially, such as thermal performance, carbon emissions (Shao, Li, Zhou, Hu, et al., 2021), perception of noise (Van Renterghem, 2019), and impacts on air quality (Wesoowska & Laska, 2019). Other issues are the concept of building energy (Djedjig et al., 2016), the use of gray water (Prodanovic et al., 2017), general biowall performance (Gunawardena & Steemers, 2019), and the combination in construction (Radić et al., 2019).

The research problem focuses on the methods used to prove the performance of biowall effects on thermal, visual, audial, and respiratory comfort. The other issues are related to the ratio of the spatial dimensions and the selection of suitable plants that affect the interior atmosphere. After successfully concluding the method used to prove biowall performance, the biowall area-space area ratio, and the types of plants recommended to induce atmospheric comfort, this research aims to provide a research gap as a state-of-the-art for future researchers. On the other hand, the results of this research are expected to provide guidance and evidence that practitioners can utilize biowalls in their designs. Mainly, biowalls are used as an element of beauty and to improve atmospheric interiors biotechnologically.

Methodology

This research sequence comprises seven stages. It started with searching papers through Publish or Perish software, to obtain 100 papers and proceedings. The searching process was carried out using several combinations of keywords and titles, such as “plants,” “vegetation,” “biowall,” “living wall,” “vertical greenery,” “green facade,” “interior,” and “indoor plant”. The minimum target number of papers reviewed is 50 papers. This figure is considered quite representative and can be used to generalize findings. Therefore, an initial screening of 100 papers was carried out to avoid the number of papers being less than 50 due to manual screening based on review topics. The data sources used are Scopus and the results were obtained 100 papers from 2016 to 2021. The goal is that the articles reviewed are under current environmental conditions, work atmosphere, and user characteristics, hence the output is suitable for its application presently and in the future. The next stage was manual screening by sequentially reading the 50 selected papers based on the research topic, method, and species used, as well as the ratio of space and biowall.

This was followed by analyzing the first and second cycle coding as well as data visualization using NVivo. The first cycle coding represented the article’s condition’s descriptive process and values. The descriptive coding was carried out based on nouns to indicate the plant species used in each article. Meanwhile, the process and value coding are extracted based on the verbs and values to show the method and amount of the biowall area. The second cycle coding is determined by generalizing the data for plant species, category for method and size of biowall, and inference of relationship for each node. Furthermore, the data visualization is obtained and interpreted explicitly before it is analyzed based on self-opinions and criticisms to get an enriching conclusion on the three main topics of this research.

The green wall is the most common terminology used by 18 papers (N = 50), while the exterior was the favorite place with 34 papers (N = 50) compared to the interior, which only amounted to 11 papers (N = 50). The most years distribution was in 2016 and 2020 with 12 (N = 50) and 11 papers (N = 50). Finally, a favourite topic was associated with the biowall of thermal comfort, comprised of 27 papers (N = 50).

Findings And Discussion

Biowall Method

The experimental method is the most widely used with 36%. This was followed by the case research, laboratory test, and simulation methods by 34%, 20%, and 10%. The most common experimental method is making a test chamber with material suitable for in situ conditions. Furthermore, biowall needs to be added to the test room according to specific dimensions, criteria, and characters. The initial conditions of the test chamber were determined using a calibrated instrument according to the variables studied while measuring the variables. The analysis step compares measurement results with and without biowall (Thomazelli et al., 2017; Pan et al., 2020; Zhang et al., 2019; Romanova et al., 2019). Another experimental method is making a test room after reducing the actual size to analyze the condition of the test chamber, as the experimental method uses an accurate scale.

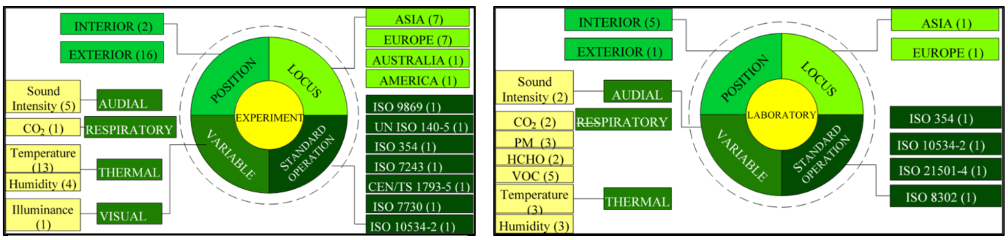
Fig. 1a shows the second cycle coding categorization results using Nvivo further generated 18 articles, which used the four comfort variables separately. The highest sub-variables tendency was the temperature variable for thermal comfort, with a value of 17, and the sound intensity variable for audial comfort, which had five reviews. This data shows that previous research rarely discussed respiratory and visual variables. The sub-variable for respiratory comfort used in the experimental method was only CO_2 levels, while the visual comfort utilized the illuminance factor.

Comforts are formed from the response of the human sense, such as the eyes, ears, nose, tactile, heat, and brain. This condition is not absolute but varies depending on the individual’s metabolism, activity, and the body’s ability to adapt. Most research discussed the ability of biowall to provide partial comfort based on a body sensor, which does not fit in real life. The experimental method allowed more variables to be tested.

In terms of position, the distribution data shows the exterior and interior by 16 (N = 18) and 2 (N = 18). It is a new potential to explore the impact of biowall on the interior, while European and Asian countries dominate the locus of research. Presently, no research has been conducted in Africa hence it has become a new novelty to compare two continents with different climates using the same experimental concept.

At least seven international standards were used as a standardized reference in the experimental method. The ISO 9869 (1994) standard measured the thermal resistance and transmission (Bianco et al., 2017), while the ISO 7243 (2017) determined the Wet Bulb Globe Temperature (WBGT) index (Feitosa & Wilkinson, 2020). Other thermal standardization is ISO 7730 (Widiastuti et al., 2020). Furthermore, the sound absorption coefficient in the Kundt tube was measured using the ISO 10534-2 standard (Serra et al., 2017). Acoustic testing was conducted on each UNE-EN ISO 140-5 (Pérez et al., 2016), ISO 354 (Thomazelli et al., 2017) and CEN/TS 1793-5 acoustic measurement standards (Romanova et al., 2019).

The experimental results improved the measured variables significantly but in various magnitude variations because there are no clear criteria in each research. Linear comparisons cannot analyze the results because the methods differed. The ambiguity includes the dimensions of the test chamber, its material, the substrate and type of plant, the biowall area, the determination of the measuring point, the instrument, the position of the test chamber, measurement time, and the method for analyzing the measurement results. Clear standardization is needed in the future, and comparing several standards in an article could be a new enrichment of knowledge.



a. Matrix Coding for Experimental Method b. Matrix Coding for Laboratory Method

Fig. 1

Matrix Coding for Experimental and Laboratory Method

Laboratory experiments using a room atmosphere closed control system is shown in Fig. 1b. The test chamber of the second cycle coding of the laboratory method is a sealed glass chamber (Cáceres & Urrestarazu, 2021; Cáceres et al., 2021; Sowa et al., 2019; Pettit et al., 2017; Pettit et al., 2018), a mini box with less than 1 m3 space (Libessart & Kenai, 2018) or a real space (Moya et al., 2021). The principle works by continuously flowing the test chamber with certain variables, then comparing the measurement results with and without plants. The standards used in this research are ISO 10534-2 and ISO 354for acoustic procedures (Attal, Côté, et al., 2019), ISO 8302 for thermal methods (Libessart & Kenai, 2018), ISO 21501-4 for respiratory performance (Assimakopoulos et al., 2020).

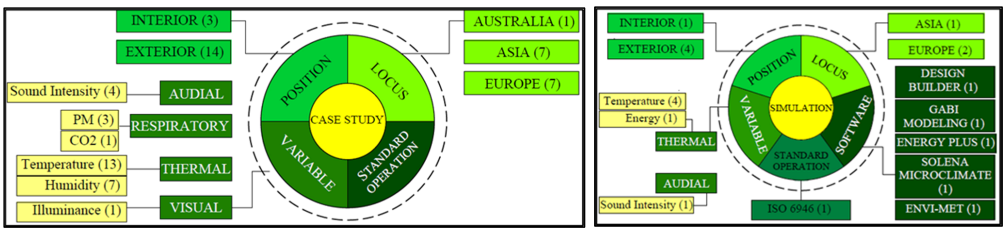
The matrix coding results for laboratory methods shown in Fig. 1b indicate that the most studied variable is the respiratory comprising variants levels of PM, HCHO, VOC, and CO_2. Five articles (N=10) specifically discussed the impact of biowall on VOC levels with the object placed in the interior, a closed glass room, or a mini box. The locus was detected in Asia and Europe, while others were not clearly stated. Therefore, further research must provide clear locus information to generalize the findings. Furthermore, literature review need to be appropriate in determining sources of articles distributed in various countries. Data distriubtion shows that preliminary research have been carried out on two comfort variables, namely thermal and respiratory. Therefore, future research needs to be conducted by comparing the results from multiple countries with different climates.

Another method is a case study on the reality of building that use biowall. As shown in Fig. 2a, case studies on the reality of buildings are done in various climates and regions of the world, such as Europe, Asia and Australia. It was specifically carried out in Germany (Hoelscher et al., 2016), China (Peng et al., 2019; Shao, Li, Zhou, Zhang, et al., 2021; Li et al., 2019), Spain (Urrestarazu et al., 2016; de Jesus et al., 2017), Indonesia (Widyahantari et al., 2020; Kristanto et al., 2021), Hong Kong (Wong & Baldwin, 2016), Sydney (Paull et al., 2020), Japan (Abe et al., 2020), Paris (Lunain et al., 2016), Eindhoven (Liu et al., 2021), Slovakia (Poorova et al., 2018) and Czech (Weerakkody et al., 2018).

The placement of biowall objects in the case research is quite diverse when placed indoors (Urrestarazu et al., 2015; Poorova et al., 2018; Shao, Li, Zhou, Hu, et al., 2021) and outdoors (Hoelscher et al., 2016; Peng et al., 2019; Li et al., 2019; de Jesus et al., 2017; Widyahantari et al., 2020; Kristanto et al., 2021; Wong & Baldwin, 2016; Paull et al., 2020; Abe et al., 2020; Lunain et al., 2016; Liu et al., 2021; Weerakkody et al., 2018; Shimizu et al., 2016; Tudiwer & Korjenic, 2017). Some research used universities and schools as research objects (Hoelscher et al., 2016; Li et al., 2019; Urrestarazu et al., 2016; Paull et al., 2020; Poorova et al., 2018), while others are located in high-rise apartments, condominiums (Wong & Baldwin, 2016; Paull et al., 2020; Abe et al., 2020; Liu et al., 2021), museums (de Jesus et al., 2017), open spaces (Lunain et al., 2016; Weerakkody et al., 2018), and office buildings (Peng et al., 2019; Shao, Li, Zhou, Zhang, et al., 2021; Widyahantari et al., 2020; Kristanto et al., 2021). The research's working principle was to compare the measurement results of the variables studied between in-situ buildings with and without biowall.

Fig. 2

Matrix Coding for Case Study and Simulation Method



a. Matrix Coding for Case Study Method b. Matrix Coding for Simulation Method

The operating standards of this research are essential for readers to ensure the results obtained are accountable and under applicable scientific principles. Operational research standards do not always have to be international, but local standards of each region or each country can be another alternate use with a clear explanation.

Simulation using specific software is also another effort to prove the performance of the biowall. The GaBi Modeling (Mannan & Al-Ghamdi, 2020), Energy Plus (Dahanayake & Chow, 2017), a combination of EnergyPlus with Design-Builder (Assimakopoulos et al., 2020), Envi-met (Li et al., 2021), and Solene-microclimate (Musy et al., 2017) are software used to determine the Life Cycle Assessment (LCA), energy-saving potential, and thermal simulation of biowall. Comparisons between experimental methods and software simulations facilitate data analysis (Li et al., 2021).

Fig. 2b shows the distribution of the coding for the simulation method. All software used in previous research only discussed thermal audial-related topics. There fore future research needs to simulate other comforts such as visual, and respiratory. Another novelty is creating new software that combines several comfort elements as an output rather than using existing software.

Biowall Area

Experiments with test chambers resembling real-scale in situ conditions were conducted with various sizes. The following are some of the dimensions of the test room (W x D x H) used in this research without apparent reasons. The sizes are 2 m x 1.8 m x 1.8 m (Bianco et al., 2017), 3 m x 3 m x 3 m (Coma et al., 2017), 5.1 m x 3.1 m x 3.1 m (Manso & Gomes, 2016), 0.8 m x 2.45 m x 2.45 m (Šuklje et al., 2016), 2.5 m x 4 m x 2.9 m (Serra et al., 2017), 3.8 m x 7.8 m x 3 m

(Shao, Li, Zhou, Hu, et al., 2021), and 3 m x 3 m x 3 m (Pérez et al., 2016). The size of the test room in Experiments with downsizing scales is more varied, starting with rectangle and square measuring 1 m x 1 m x 1 m (Widiastuti et al., 2020; Djedjig et al., 2016; Kristanto et al., 2020) and 1.5 m x 1.2 m x 1 m (Feitosa & Wilkinson, 2020). The determination of the test room size and the reasons are not explained based on standards and procedures.

Similarly, with the area of the biowall, there is no specific explanation regarding the standard of measurement in the test chamber. In the thermal test, some research utilized nine plant modules with a size of @ 0.4 x 0.5 m2 (Bianco et al., 2017), while others covered the entire surface of the façade wall with biowall (Coma et al., 2017). Davis et al. made use of ten modules @ 0.45 x 0.45 m2 to collect and spread positions in the room in the audial test (Davis et al., 2017). Meanwhile, Thomazelli et al. utilized 20 modules with a total area of 7.2 m2 (Thomazelli et al., 2017). In another research related to visual testing, the size of the plant module was identified from the Leaf Area Index (LAI) (Kristanto et al., 2020) or by comparing the use of plants LAI > 3 with LAI < 1 (Kristanto et al., 2021). Several others did not mention the area of the biowall explicitly in the respiratory test (Pettit et al., 2018), but a hydroponic system measuring 1.43 m x 1.9 m was utilized (Shao, Li, Zhou, Hu, et al., 2021).

Fig. 3 shows the experimental method's matrix coding for the biowall and room area. All 18 research provided precise information without giving a clear basis for selecting these dimensions. There is no standard for operational biowall for research applications and real projects. This is a new opportunity for future research to be conducted to obtain a deeper ratio of practical biowall area requirements for a specific volume of space. This finding is important because it can be used as a reference for architects on real projects.

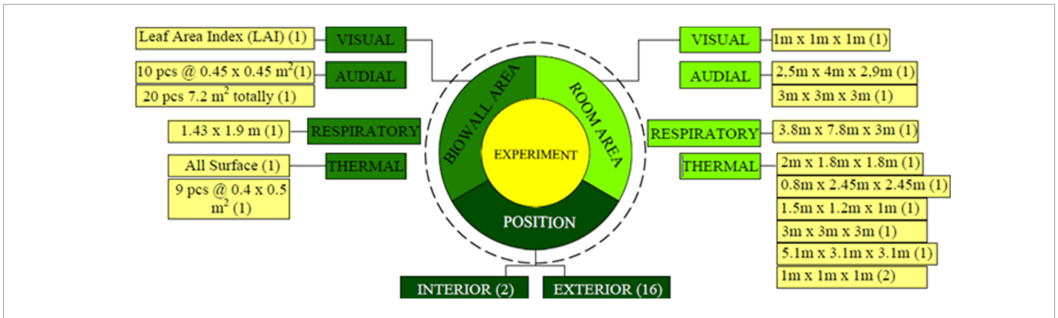


Fig. 3
Matrix Coding for Experimental Biowall Area

The size of the test chamber, the area, and the comparison between the two will affect the results of the performance of the biowall. These three issues need to be determined to apply the positive biowall results based on specific global parameters. Table 1 shows reference papers, including the nomenclature of the biowall, the research method, its position, operational standards, locus, object, software manipulated, dimensions of the test room, and the main variables tested.

Table 1
Research Mapping

Method, Standardization	Position, locus	Type of plant	Object/Software/Dimension	Main Variable	Author(s)
Case Study, (ND)	Exterior, Sydney	ND	Apartment /Condominium	Temperature, Sound, PM	(Paull et al., 2020)
Experiment, ISO 7243(2017)	Exterior, Sydney	Succulent (*Crassula Lycopodioides, Echeveria, Pachyveria*), small flower (*Sedum, Tradescantia*)	Test Chamber 1.5x1.2x1 (m^3)	Temperature	(Feitosa & Wilkinson, 2020)
Case Study, ND	Interior, Slovakia	ND	University /School	Temperature, Humidity	(Poorova et al., 2018)

Method, Standardization	Position, locus	Type of plant	Object/Software/Dimension	Main Variable	Author(s)
Experiment, ND	Exterior, Spain	Small Flower (*Helichrysum Thianschanicum*), Bush (*Rosmarinus Officinalis*)	Test Chamber 3x3x3 (m^3)	Temperature	(Coma et al., 2017)
Experiment, ND	Exterior, Portugal	Shrub (*Thymus Mastichina, Thymus Prostratus, Thymus Serpyllum, Thymus Vulgaris*), small flower (*Archillea Millefolium, Sedum Album*)	Test Chamber 5.1x3.1x3.1 (m^3)	Temperature	(Manso & Gomes, 2016)
Experiment, ND	Exterior, Athens	ND	Test Chamber 1x1x1 (m^3)	Temperature, Humidity	(Djedjig et al., 2016)
Experiment, ISO 354	Exterior, -	Perennial (*Callisia Repens*)	Test Chamber	Sound	(Thomazelli et al., 2017)
Simulation, ISO 6946	Exterior, Athens	ND	Energyplus + Design Builder	Temperature	(Assimakopoulos et al., 2020)
Simulation, ND	Exterior, France	ND	Solene Microclimate	Temperature	(Musy et al., 2017)
Laboratory, ISO 10534, ISO 354	ND	Small Flower (*Japanese Spindle*)	Stainless Steel Tube	Sound	(Attal, Côté, et al., 2019)
Laboratory, ND	ND	Small Flower (*Japanese Spindle*),	Stainless Steel Tube	Sound	(Attal, Cote, et al., 2019)
Laboratory, ISO 8302	Exterior	Succulent (*Ivy*), Vines (*Virginia*)	Minibox	Temperature	(Libessart & Kenai, 2018)
Laboratory, ND	Interior, Mashhad	Vines (*Peperomia*) Succulent (*Aptenia Cordifolia, Carpobrotus Edulis, Kalanchoe Blossfeldiana*)	Laboratory Room	Temperature, Humidity	(Kazemi et al., 2020)
Laboratory, ISO 21501-4	ND	Fern (*Nephrolepis Exaltata Bostoniensis*)	Glass Chamber	HCHO, VOC, PM levels	(Pettit et al., 2018)
Laboratory, ND	ND	Fern (*Nephrolepis Cordifolia Duffii, Nephrolepis Exaltata*), Tree (*Ficus Lyrata*), Epiphyte (*Nematanthus Glabra*), Small Plant (*Schefflera Amate-Arboricola, Chlorophytum Orchidastrum*)	Glass Chamber	PM levels	(Pettit et al., 2017)
Case Study, ND	Exterior, Germany	Succulent (*Hedera Helix*), small flower (*Fallopia Baldschuanica*), Vines (*Parthenocissus Tricuspidata*)	University /School	Temperature	(Hoelscher et al., 2016)
Case Study, ND	Exterior, Hongkong	Vines (*Virginia Creeper*)	Apartment /Condominium	Temperature	(Wong & Baldwin, 2016)
Case Study, ND	Exterior, Yokohama	Vines	Apartment /Condominium	Temperature	(Abe et al., 2020)
Case Study, ND	Exterior, Dujiangyan	Vines	Office	Temperature, Humidity	(Peng et al., 2019)
Experiment, ISO 354 CEN/TS 1793-5	Exterior, -	Succulent (*Bergenia Crassifolia, Hedera Helix*)	Test Chamber	Sound	(Romanova et al., 2019)

Method, Standardi-zation	Position, locus	Type of plant	Object/Soft-ware/Dimension	Main Variable	Author(s)
Experiment, ND	Exterior, China	Vines (*Pyrostegia Venusta*)	Test Chamber	Temperature, Humidity	(Zhang et al., 2019)
Experiment/ Simulation, ND	Exterior, China	Succulent (*Hedera Helix*)	Envi-met dan Test Chamber	Temperature	(Li et al., 2021)
Experiment, ND	Exterior, Tehran	Water Plant (*Azolla*)	Test Chamber	Temperature	(Parhizkar et al., 2020)
Experiment, ND	Exterior, Indonesia	Succulent (*Ivy*)	Test Chamber 1x1x1 (m^3)	Illuminance, Temperature, Humidity	(Kristanto et al., 2020)
Experiment, ND	Interior, China	ND	Test Chamber 3.8x7.8x3 (m^3)	CO_2	(Shao, Li, Zhou, Hu, et al., 2021)
Laboratory, ND	Interior, -	Fern (*Nephrolepis Exaltata* L)	Laboratory Room	Temperature, Humidity, CO_2, VOC	(Moya et al., 2021)
Laboratory, ND	Interior, -	Vines (*Epipremnum Aureum*), Bush (Dieffenbachia *Seguine*), Succulent (*Sansevieria Trifasciata*)	Glass Chamber	Humidity, PM CO_2, VOC,	(Sowa et al., 2019)
Case Study, ND	Interior, Spain	Epiphyte (*Monstera Deliciosa Liebm, Nematanthus Glabra*), Fern (*Nephrolepis Exaltata*), Perennial (*Asparagus Sprengeri, Regel Callisia Repens*), Small Plant (*Chlo-rophytum Comosum*), Vines (*Epipremnum Aureum, Ficus Pumila L, Soleirolii*)	University /School	Temperature, Humidity	(Urrestarazu et al., 2016)
Simulation, ND	Interior, -	ND	Gabi Modeling	Energy Effi-ciency	(Mannan & Al-Ghamdi, 2020)
Case Study, ND	Exterior, Spain	ND	Museum	Temperature	(de Jesus et al., 2017)
Experiment, ND	Interior, Eciador	Ferns	Test Chamber	Sound	(Davis et al., 2017)
Experiment, ISO 7730	Exterior, Indonesia	Small Flower (*Passiflora Flavicarva*), Bush (*Pseudocalymma Alliaceum*)	Test Chamber 1x1x1 (m^3)	Temperature, Humidity	(Widiastuti et al., 2020)
Case Study, ND	Exterior, Czech	Small Flower (*Acorus Gramineus Sol*),	Open Space	PM	(Weerakkody et al., 2018)
Case Study, ND	Interior, Nanjing	Tree (*Chamaedorea Elegans Mart*), small flower (*Fatsia Japonica, Schefflera Octophylla* (Lour.))	Office	Temperature, CO_2, PM, Humidity	(Shao, Li, Zhou, Zhang, et al., 2021)
Laboratory, ND	Interior, Spain	Fern (*Nephrolepis Exaltata*)	Glass Chamber	VOC	(Cáceres et al., 2021)
Laboratory, ND	Interior, -	Perennial (*Spathiphyllum Wallisii*), Small Flower (*Chlorophytum Comosum, Tradescantia Pallida*), Vines (*Ficus Pumila, Philodendron Hederaceum*)	Glass Chamber	HCHO, VOC	(Cáceres & Urrestarazu, 2021)
Case Study, ND	Exterior, Indonesia	Small Flower (*Passiflora*)	Office	Temperature	(Widyahantari et al., 2020)
Case Study, ND	Exterior, Indonesia	Fern (Equisetum), Bamboo (*Shibataea*)	Office	Illuminance, Temperature	(Kristanto et al., 2021)

Method, Standardi-zation	Position, locus	Type of plant	Object/Soft-ware/Dimension	Main Variable	Author(s)
Experiment, ND	Exterior, Slovenia	Bush (*Phaseolus Vulgaris*)	Test Chamber 0.8x2.45x2.45	Temperature	(Šuklje et al., 2016)
Experiment, ISO 140-5	Exterior, Spain	Small Flower (*Helichrysum Thianschanicum*), Bush (*Rosmarinus Officinalis*)	Test Chamber 3x3x3 (m^3)	Sound	(Pérez et al., 2016)
Experiment, ND	Exterior, Hong-kong	Tree (*Codiaeum Variegatum, Ficus Elastica), Succulent (Sansevieria Trifasciata*), small flower (*Coleus Blumei, Duranta, Rhoeo, Schefflera Octophylla), Vines (Peperomia Claviformis*)	Test Chamber	Temperature	(Pan et al., 2020)
Simulation, ND	Exterior, Hong-kong	ND	Energyplus	Temperature	(Dahanayake & Chow, 2017)
Experiment, ISO 9869 1994	Exterior, Italy	Succulent (Bergenia Cordifolia), small flower (Lonicera Nitida)	Test Chamber 2x1.8x1.8 (m^3)	Temperature	(Bianco et al., 2017)
Experiment, ISO 10534-2	Exterior, Italy	Perennial (*Heuchera Hybr*), Succulent (*Bergenia Cordifolia), small flower (Lonicera Nitida*)	Test Chamber 2.5x4x2.9 (m^3)	Temperature, Sound	(Serra et al., 2017)

Plant Species of Biowall

The main reason for the selection criteria of plant species in biowall is the ability of plants to respond to the atmosphere of space and ease. The convenience includes easy of finding, adaptability, adequate maintenance, and ease of breeding. Biowall with vines was selected in the thermal conditions in the room atmosphere due to its fast growth and maximum height.

Fig. 4a shows the matrix coding for thermal comfort regarding plant species, which were discussed by 19 of the 50 articles. Eleven plants used it for thermal comfort, with only water plant, shrub and tree utilized for the temperature test. Although thermal comfort is the most favorite topic to be discussed with diverse vegetation species, research have not been conducted on the medicine plant and vegetable plant species consumed by humans, such as lettuce, pokcoy, tomatoes, and carrots. This type may be developed in the future, primarily if it is associated with independent urban agriculture. The vegetable plant will obtain economic value with more specific lighting mechanisms and biowall treatment.

The mechanism of plants in the biowall that affects temperature is the process of evapotranspiration (Moya et al., 2017), which is affected by physical factors, such as temperature, atmospheric pressure, solar radiation, water vapor pressure, and wind speed. This process is also affected by vegetation factors, including plant species, active root depth, and stomata type. Plants are widely discussed as an alternative to decreasing internal thermal problems, especially in urban areas. Glass, as a favorite material, increases the interior temperature significantly due to sunlight penetration (Purwanto & Tichelmann, 2018).

The vines that affect temperature and humidity are Boston ivy (Libessart & Kenai, 2018; Li et al., 2019), *Epipremnum aureum, Ficus pumila, Soleirolia soleirolii* (Urrestarazu et al., 2016), *Fallopia baldschuanica, and Parthenocissus tricuspidata* (Hoelscher et al., 2016). Hedera helix (Hoelscher et al., 2016; Li et al., 2021), *Thymus prostratus, Thymus serphyllum* (Manso & Gomes, 2016), Virginia creeper (Libessart & Kenai, 2018; Wong & Baldwin, 2016), Passiflora (Widiastuti et al., 2020; Widyahantari et al., 2020), *Pseudocalymma alliaceum* (Widiastuti et al., 2020), *Pyrostegia venusta* (Zhang et al., 2019), and Tradescantia (Feitosa & Wilkinson, 2020). Thermal tests used small flowering plants such as *Aptenia cordifolia, Kalanchoe blossfeldiana* (Kazemi et al., 2020), *Crassula lycopodioides*, Sedum (Feitosa & Wilkinson, 2020), *Thymus mastichina, Thymus vulgaris, Sedum album* (Manso & Gomes, 2016), *Bergenia cordifolia* (Bianco et al., 2017), and C*hlorophytum comosum* (Urrestarazu et al., 2016). Other thermal tests used succulent species such as *Carpobrotus edulis* (Kazemi et al., 2020) and Pachyveria (Feitosa & Wilkinson, 2020). This is in addition to using epiphytic species, such as *Monstera deliciosa* Liebm (Urrestarazu et al., 2016), aquatic plant species, including Azolla (Parhizkar et al., 2020), and fern species like *Nephrolepis exaltata* (Urrestarazu et al., 2016). The shrub species comprises *Achillea millefolium* (Manso & Gomes, 2016), *Lonicera nitida, Helichrysum thianschanicum, Rosmarinus officinalis* (Coma et al., 2017), *Phaseolus vulgaris* (Šuklje et al., 2016), *Asparagus sprengeri* Regel (Urrestarazu et al., 2016), *Codiaeum variegatum, Coleus blumei,* Duranta, *Ficus elastica,* Peperomia, Rhoeo, *Sansevieria trifasciata, Schefflera octophylla* (Pan et al., 2020), Echeveria, and Peperomia (Kazemi et al., 2020).

The surface temperature of the outer wall with biowall achieves 15.5°C lower than the bare in terms of thermal performances, while the interior wall reaches 1.7°C (Hoelscher et al., 2016). The existence of the Vertical Greenery Modular System can reduce heat and energy performance by 23 °C and 40% (Bianco et al., 2017). The simulation using Energy Plus around the Hong Kong area proves that the Vertical Greenery System can reduce the temperature of the building facade in summer, by 26 °C or by 3% of cooling energy consumption (Dahanayake & Chow, 2017). Using an active living wall in a university hall in Spain reduced the interior temperature by 0.8°C and 4.8°C at different distances (Urrestarazu et al., 2016). Geogreens in a Mediterranean climate reduce the average daily interior and surface thermal amplitude by 11.3°C and 15°C during summer (Manso & Gomes, 2016).

People can use several types of plants to induce visual atmospheric conditions. Examples include vines, bamboo, and tree plants as an alternative for visual conditioning of space. Ivy is one type of vine for this purpose (Kristanto et al., 2020). This is in addition to using bamboo species such as Shibataea (Kristanto et al., 2021) and Equisetum (Peng et al., 2019) for the other three plant species.

The greenery facade in the tropical area with a west orientation can reduce sunlight by 31.18 to 51.71 % (Kristanto et al., 2020). Meanwhile, a facade without plants in a southern orientation lowers it by 28.4 to 54.87 %. The Vertical Greening System for the Shibataea plant species has been proven to be able to reduce the average interior air temperature by 0.5 to 2°C, with a maximum temperature difference of 5°C, at a light reduction of 26.95% (Kristanto et al., 2021).

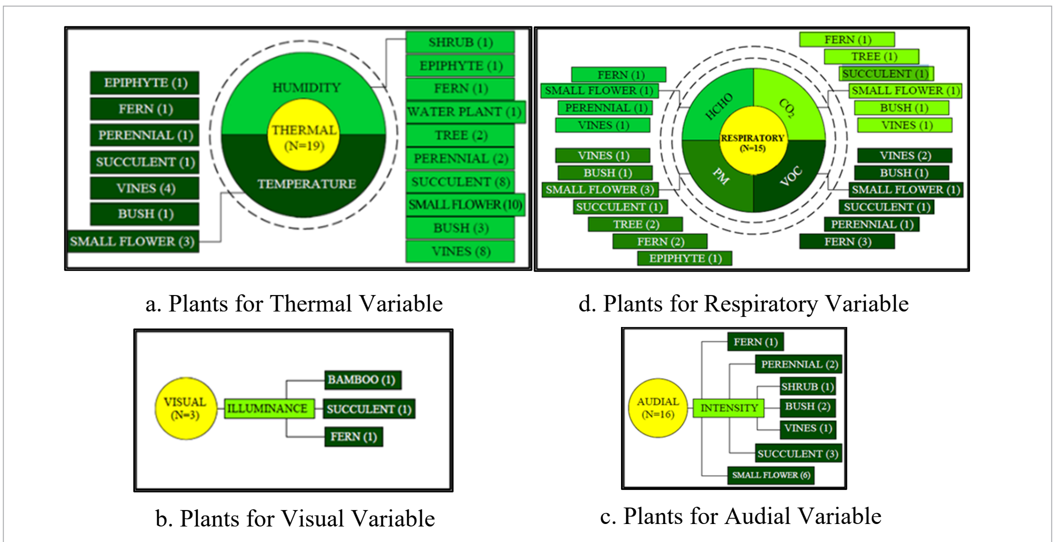


Fig 4

Matrix Coding for Plants Species of Thermal Comfort

Fig. 4b shows the distribution of matrix coding for plant species related to visual comfort. Only three articles reviewed the correlation between biowall and visuals, which means research on this topic are still very rare. There were no species of vines, shrubs, and bushes found in this topic. The mechanisms that affect visual quality include the characteristics of green plants with thick and broad leaves as well as their height and density exposed to light. Therefore, it is a bit inappropriate for this topic to use bamboo and equisetum species because the typical leaves are small and not dense.

The species used to determine the audial conditions are floral and non-flowered shrubs, with and without vines, which densely grow with thick leaves. The types of small floral plants used are *Ardisia japonica, Leucothoe catesbaei, Liriope platyphylla* (Shimizu et al., 2016), *Bergenia crassifolia* (Romanova et al., 2019), E*uonymus japonicus* (Attal et al., 2021), *Heuchera hybrid, Bergenia cordifolia* (Serra et al., 2017), and Japanese spindle (Attal, Côté, et al., 2019). Species of vines use *Hedera helix* (Romanova et al., 2019; Shimizu et al., 2016) and *Callisia repens*, while shrub plants can use Hedera canariensis (Shimizu et al., 2016), *Helichrysum thianschanicum, Rosmarinus officinalis* (Pérez et al., 2016), Lonicera nitida (Serra et al., 2017), and ferns species (Davis et al., 2017).

Fig. 4c shows the distribution of the coding matrix for the audial comfort regarding plant species using various types of plants. The mechanism of plants in affecting noise depends on their performance in absorbing, diffracting, and reflecting sound (Gunawardena & Steemers, 2019) using stems, leaves, and woody branches. Factors that affect sound absorption by plants are the number, size, and leaf surface area. Plants ideal for reducing noise are thick, broad-leaved plants.

In terms of audial condition, the performance of the biowall in the echo chamber laboratory was carried out using soil composition as a good sound absorber (Shimizu et al., 2016). The sound absorption coefficient at low, medium, and high frequencies of 100 to 315 Hz, 400-1250 Hz, and 1600-5000 Hz are 0.59 to 0.80, 1.00, and 1.00, with the addition of a substrate and a fern on a wall in a University test room in Ecuador (Davis et al., 2017). The average acoustic absorption coefficient by simulation using a system thickness of 16 cm, green facade, and living system modular walls are 0.2 (300-1000 Hz), 0.2 (200-1000 Hz), and 0.9 (300-1000 Hz) (Attal, Côté, et al., 2019). There is a significant increase in the sound absorption coefficient across the spectrum when using substrates and plants (Thomazelli et al., 2017). The plant layer on the green wall (polyethylene material) and façade with wire mesh of 20-30 cm can increase sound insulation of 1 dB for traffic noise and an increase in insulation between 2 dB to 3 dB for pink noise (Pérez et al., 2016).

Nephrolepis cordifolia Duffii (Pettit et al., 2017) and *Nephrolepis exaltata* (Cáceres & Urrestarazu, 2021; Pettit et al., 2017; Pettit et al., 2018; Moya et al., 2021) were used for respiratory comfort. Other plants include perennial species (*Spathiphyllum wallisii*) (Weerakkody et al., 2018) vines, small flowering plants, and shrubs. The vine species such as *Epipremnum aureum* (Sowa et al., 2019), *Philodendron hederaceum* (Cáceres & Urrestarazu, 2021), and *Ficus pumila* L (Cáceres & Urrestarazu, 2021). Species of small-flowered plants such as *Acorus gramineus* (Weerakkody et al., 2018), *Chlorophytum orchidastrum, Ficus lyrata, Nematanthus glabra, Schefflera amate, Schefflera arboricola* (Pettit et al., 2017), *Chlorophytum comosum* (Cáceres & Urrestarazu, 2021), *Dieffenbachia seguine* (Sowa et al., 2019), and *Tradescantia pallida* (Shao, Li, Zhou, Zhang, et al., 2021). Species of shrubs include *Sansevieria trifasciata* (Sowa et al., 2019), *Schefflera octophylla* (Shao, Li, Zhou, Zhang, et al., 2021), *Chamaedorea elegans* Mart, and Fatsia japonica (Shao, Li, Zhou, Zhang, et al., 2021). Table 1 shows the results of reference papers and comfort variables due to plant type.

Fig. 4d shows the distribution of the matrix coding for eight types of plant species associated with respiratory. The most important thing in this topic is using plant types with high phytoremediation ability because it determines the mechanism of plants in affecting air quality (Moya et al., 2017). Stomata carried out the air absorption system in plants during the regular gas exchange (Moya et al., 2017). Factors affecting phytoremediation are temperature, soil pH, number of plants, plant age, living time, and plant species. Phytoremediation increased by plants' number, efficiency, and age, at high temperatures, with a soil pH from 5.5 to 7.

Nephrolepis exaltata Bostoniensis on the green wall removed PM 0.3 to 0.5 levels of 45.78% and 92.46% to determine the IAQ (Pettit et al., 2017). In addition, Nephrolepis exaltata has also been proven to have the ability to reduce CO_2 levels significantly (Moya et al., 2021). Chlorophytum comosum was the most efficient species in reducing Volatile Organic Compound (VOC) concentrations in indoor spaces in Spain (Cáceres & Urrestarazu, 2021). The level of odor intensity in the interior based on active plants is higher than in the room without plants (Moya et al., 2021). The addition of a potted plant in the interior reduced VOC and formaldehyde levels by 48% and 145% (Sowa et al., 2019).

Conclusion

This research attempts to connect biowall to interior atmospheric comfort globally to ensure it provides thermal, visual, audial, and respiratory comfort. The interior atmospheric comfort depends on the types of plants and methods used to prove biowall performance to obtain varying results. More specifically, it is crucial to compare the spatial and biowall dimensions to determine their performance. The first result shows that biowall affects the interior atmosphere using various empirical methods. The method is real-scale or scale-down rooms experimental, laboratory tests, simulation using specific software, case studies on in-situ biowall, and a combination of those methods. Under prevailing procedures, each technique can be accounted for to determine the research principles.

The second result is that there is no clear standard regarding the size of space and biowall used because the different magnitudes cannot compare positive results from each research. Furthermore, there is undoubtedly a gap to determine the size of the biowall that effectively induces thermal, visual, audial, and respiratory comfort, especially for residential purposes.

The main factor of biowall to induce interior atmospheres is the type of plants. The determination criteria refer to the ability of plants to respond to atmospheric conditions, adaptability, accessible care for, and reproduction. Fern and succulents have the potential to be used to induce the atmospheric interior in terms of thermal, visual, audial, and respiratory comfort. Finally, some 'state of the art' may be necessary for further research, based on the conclusions of the literature review obtained:

- The biowall has been researched based on the body's sensors partially. Therefore, it is crucial to research biowall for holistic comfort based on multiple sensors simultaneously. The body must analyze the comfort from all five senses simultaneously because they receive different stimuli.
- Previous research empirically provided positive results on the comfort aspect of biowall performance with varying magnitudes due to room and size differences. Determination of the standard size becomes a significant research opportunity in the future for researchers and professional architects. Standardization of biowall sizes will be a real outcome that can be directly utilized by interior practitioners, architects and urban designers.
- Several researchers conducted using the software. It will be a different novelty and new research opportunity if the research output produces comfort software related to the artificial intelligence of biowall, the biowall internet of things, or the facade kinetics of biowall.
- Another finding states that the locus of research on the case study method is primarily in offices, public spaces, or apartments/high-rise residential. So, for future scientific enrichment, it is necessary to consider researching the effect of biowall on interior landed housing.
- Future research needs to determine the ability of the biowall by enriching various types of food and medicinal plants such as legumes, tubers, vegetables, ginger, and others.

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