Article

Not peer-reviewed version

Modular Green Wall Systems as a Specific Handwriting Style in Architecture of Green Buildings

Natalia Shushunova * and Elena Korol

Posted Date: 10 August 2023

doi: 10.20944/preprints202308.0809.v1

Keywords: green wall system; reducing the air pollutants; indicators of the effectiveness; green building technologies; biophilic architecture; quality of the urban environment.

Article

Modular Green Wall Systems as a Specific Handwriting Style in Architecture of Green Buildings

Natalia Shushunova [1,*] and Elena Korol [2]

[1] Department of Integrated Safety in Construction, Moscow State University of Civil Engineering, Yaroslavskoye Shosse, 26, 129337 Moscow, Russia; nshushun@gmail.com (N.S); professorkorol@mail.ru (N.S.)
[2] Department of Housing and Communal Utility, Moscow State University of Civil Engineering, Yaroslavskoye Shosse, 26, 129337 Moscow, Russia; professorkorol@mail.ru (E.A.)
* Correspondence: nshushun@gmail.com

Abstract: Today, harmful substances from the air in the cities can significantly harm to environment and human health. Modular green wall systems (MGWS) are created for air purifying function. Different green wall systems and various plant species were analyzed for this purpose. The results obtained prove that MGWS can improve the air quality by removing harmful pollutants from the air near the buildings. Urban design used to be turned greener and more sustainable using the modern technologies of modular green wall systems. This study focuses on the air-cleaning benefits provided by modular green wall systems and their assessment. This research contributes to fill existing literature gaps on the green wall systems on the buildings and biophilic architecture.

Keywords: modular green wall system; pollutants; green building technologies; biophilic architecture; quality of the urban environment

1. Introduction

Nowadays, there has been a huge demand for harmony, balancing between the world created by nature and the non-natural world, created by man through building technologies. Young people generally do not have a need for nature, as they usually think, however, many people are latent biophiles. This is a confirmation of the habit of populating one's home with an abundance of flower pots, listening to background recordings of the sound of birds or whales singing. Green plants also connect people with nature, thereby significantly reducing the pressure of the urban environment.

The biophilia as a term defined as "love to Life". The most common approach in biophilic architecture is to implement natural elements into the buildings and spaces around it. If a person spends enough time among objects near nature, then you can relax and see your state of mind to spiritual harmony. Nature allows you to relax and calm down.

While green architecture focuses primarily on reducing the environmental impact of buildings through the use of sustainable materials, energy-efficient systems, and renewable energy sources, biophilic architecture focuses more on the human experience of the built environment, seeking to improve well-being and productivity by connecting people with nature. The characteristics of "nature" such as organised complexity, peril, improves building design [1].

It is acknowledged that green building technologies (GBT) include: green roof and green wall systems, net-zero energy and integrated renewable energy solutions, eco-materials for building construction and smart building management products. And, as we know, GBT as a complex is a perfect tool for the sustainable development in the construction. GBT innovations are highly valued, they are driving force [2].

As key elements of "carbon neutrality", innovations in technologies of green buildings help enterprises to conserve and reduce energy expenditures [3]. Nowadays the building carbon emissions

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 August 2023 doi:10.20944/preprints202308.0809.v1

constitute a significant part of the total emissions. For example, in China these emissions exceed two billion tons, that is constituted 46.5% of the total emissions [4].

Rapid industrial development makes humanity think about the use of clean and green technologies now [5]. The indirect application of nature in biophilic architectural architecture is the development of new economic resources available to architects who use natural resources in their projects: stone, earth, plants, wood. If the workplace is filled with plants, then this will improve the mood and health of the worker, which will increase his productivity and creativity. Green plants are perfect means for cleaning of air pollutions.

Nowadays total population in urban areas is rapidly growing, and it is expected to increase up to 68% by 2050. The capabilities in adsorption of air pollutants, such as formaldehyde, benzene, xylene, are defined for the different plants.

Plants surfaces act as 'living filters', the study of Yang Han and Jechan Lee describes the differences in the removal efficiency of pollutants between the plant species [6].

Vertical alignment of green wall increases their potential for air purifying. The chlorophyll content [7] and various properties of the plants in response on the stress conditions were studied [8]. The scientists from Sydney, Australia, were looking for the special species, tolerant for use in in case of very high air pollution [9].

Green walls or vertical greening could use the various substrates from the loam soil to rice husk [10].

Among the new trends in green buildings - modular green walls, and they have a great potential. Modular green technologies and systems, including modular green walls, have a lot of benefits. One of the largest advantages of the modular green systems, that modules with a built-in vertical garden are easy to install and demount, because of their mobility and light weight. Also modules can be organized like a multi-variant nature, using free-form modeling and different textures, for example, it can make implemented the biophilic ideas of authors. So, as example, Grooflab, author's project has surfaces with organic shapes - ocean waves forms. Nature-oriented urban design considers such projects with idea of biophilia because it is important to quality of our life [11].

Another benefit is possibility to integrate water irrigation system, both in each module and in the whole modular system.

Some researchers demonstrate the ability of modular green wall system (MGWS) to increase thermal insulation [12,13]. Thermal behaviour of panels with coconut fibre as an alternative core material to polyurethane was investigated [14]. In this regard, MGWS can reduce energy expenditure from the buildings [15,16].

Furthermore, the application of modern technologies such as smart buildings with combination of artificial intelligence and big data analytics is shaping the future trajectory of in the construction industry, including the influence on future generations [17–20].

Recent studies showed that MGWS could effectively reduce NO2, SO2, O3 and CO [21]. The major sources of air pollutants are building materials, chemicals and combustion by products, including carbon monoxide, nitrogen and sulfur dioxides, formaldehyde and tobacco smoke. Huge complex of chemicals, like benzene, formaldehyde, trichloroethylene, all potential carcinogens and irritants, harmful biological contaminants we exhale every day without even thinking about it [22]. So, released from foam, insulation, glues - formaldehyde is the cause of a great deal of coughing, allergic reactions, dizziness, etc. Carbon monoxide (CO) as combustion of all carbon fuels can lead to headaches, impairment of respiration, mental disorder, and in many cases very high concentration can cause death [23].

And what about air purifying plants? How do they behave? When air is polluted with such harmful substances as sulfur dioxide, hydrogen sulfide, ozone, nitrogen dioxide, ethylene, ammonia, heavy metals, acid aerosols, aldehydes, cement dust, pollutants cause acute and chronic damage to plant leaves - necrosis. Acute injuries are characterized by plasmolysis and death of individual cells, inhibition of individual tissue fibers. Chronic damage is characterized by a change in the color of the leaves of plants. So, when damaged by sulfur dioxide, whitening occurs, with ammonia - yellowing, hydrogen sulfide - "coffee" spots appear, ozone - dotted pigmentation of the leaves.

 doi:10.20944/preprints202308.0809.v1

Green plants help human to feel at one with nature, we do not even notice, but they trap harmful substances from the air, thereby purifying it [24–28]. The leaves of plants, their roots, substrate filling and microbes work together to trap harmful substances: harmful pollutants are moved to the root zone, where they are processed (eaten) by microbes, which can use pollutants as a food source.

Species of plants that are most effective at removing all pollutants together – benzene (cancer-causing chemical), formaldehyde, trichloroethylene - are Bamboo Palm and English Ivy. Arrowhead vine, Chrysanthemums, Snake plant, Janet Craig, Massangeana (Dracaena) trap formaldehyde, benzene, toluene and xylene. Peace lily removes acetone, benzene, trichloroethylene and xylene. Gerbera Daisy is really good remover of benzene and absorbs carbon dioxide, which gives a lot of oxygen at night. Some plants, acting against common pollutants, may be toxic if touch it (or swallow): Rubber Plant, Leopard Lily [23].

In this study, various MGWS were analyzed to determine the most effective MGWS and the best plants, intended for them, for air purification.

2. Materials and Methods

MGWS (or green walls) differ from green facades in that the plants are rooted in a structural support that is attached to the wall. Many species and types of plants are tolerated the high life in a green wall, from herbs to grasses and ferns. Experimental tests can also help to analyze these systems in building structures [29–31].

Such systems can function both without water irrigation systems, and have built-in micro-drip irrigation systems, in which case water can be delivered from central water supply systems, or supplied from a special water tank where water is pumped with a pump, and then through pipes laid inside the green walls, goes to each plant. The unused water can be discharged through a special drain and, after cleaning, re-supplied for watering plants.

In this research we were estimated four modular green wall systems: Grooflab, Biotecture, Vertis and Scotscape. The detailed estimation is shown below.

2.1. Grooflab MGWS

The present MGWS, invented by authors, has unique configuration of the modules for urban spaces. Irrigation control systems and hydroponics in agriculture of greenhouses are technically successful commercial practices in many parts of our planet (Figure 1).

Figure 1. Panel (module) of Grooflab modular system, patented by authors.

The biophilic design of invented green wall system is oriented on the «Love-to-nature» conception. Panels of green walls include special constructive elements, inspiring by Renaissance, based on the totality of measurements of simple forms that are found in nature: golden ratio, Divine proportion, ocean waves form.

These modules of green wall system have a biophilic design, associated with the golden ratio (see Figure 2 a,b). In addition, to options that are different in shape in plan, there is an option with an inclination relative to a vertical surface. For the design of the structure, the option with a slope was chosen, since changing the degree complicates the design - and if this design is feasible, then options

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 August 2023 doi:10.20944/preprints202308.0809.v1

without a slope are easily feasible, involving the golden ratio and Fibonacci series. This is pleasing to the eye when looking at a modern building.

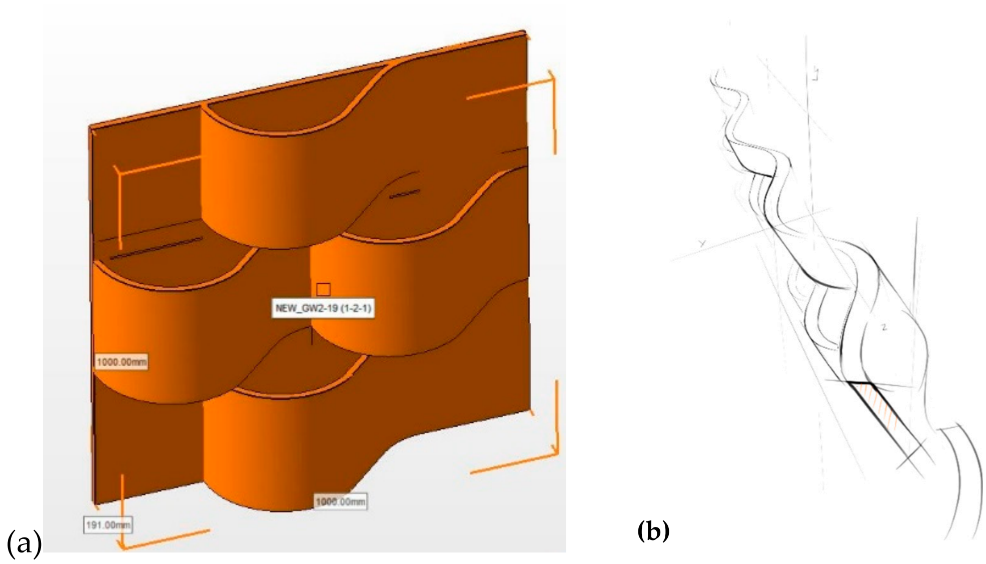


Figure 2. The biophilic design of Grooflab green wall system, patented by authors.

2.2. Biotecture MGWS

The Biotecture green wall system is formed using modules each nominally 600mm x 450mm x 62mm constructed from Polypropylene. Plants, such as ‘Irish Green’, Convolvulus cneorum, Pachysandra spp. and etc, can use for this system. 60 plants per sq m. could be built-in this MGWS. Lightweight at 70 kgs per m2 fully saturated weight [32]. The design solution of this MGWS is given on Figure 3.

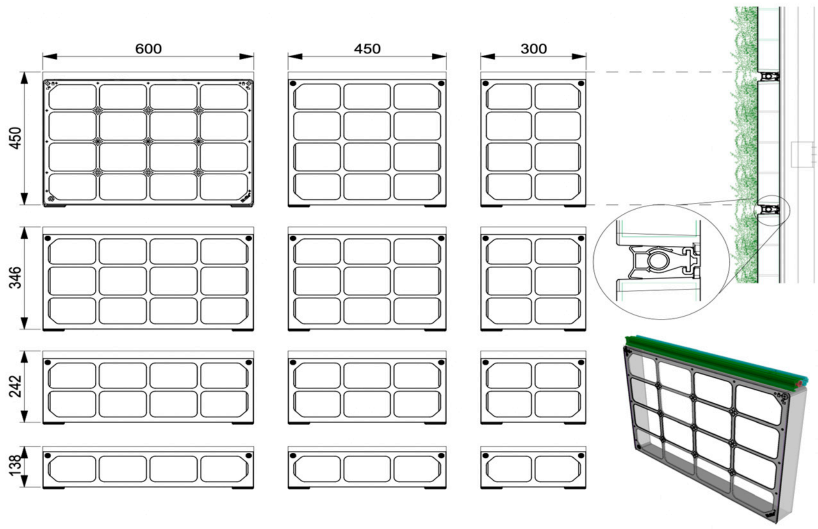


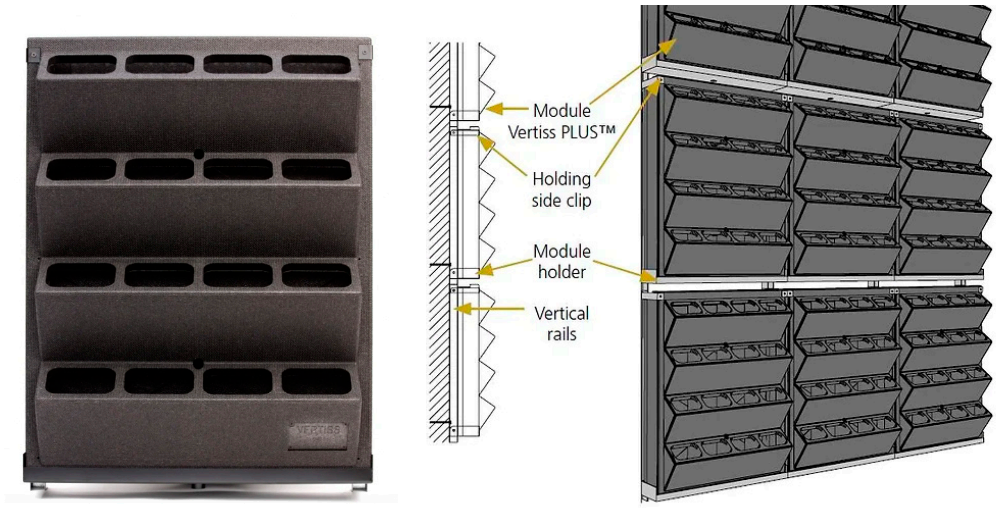
Figure 3. The modular units of Biotecture MGWS.

2.3. Vertiss MGWS

The Vertiss MGWS uses planting modules, made of HD-EPP, to create an interior living wall. This vertical green system contains the modules of 800 x 600 mm, for 16 plants.

The growing medium is organic - 30% and mineral - 70%. Irrigation system has water consumption of 2L/h. Special mosaic effect can be easily achieved over the entire MGWS [33]. The Vertiss MGWS is shown on the Figure 4.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 August 2023 doi:10.20944/preprints202308.0809.v1



(**a**) (**b**)

Figure 4. The modules of Vertiss MGWS: (**a**) 3D view, (**b**) schematic view of the system.

2.4. Scotscape MGWS

The Scotscape MGWS is a light-weight, semi-hydroponic, modular system, which consists of supporting wall, sub-frame, multi-layer modules, irrigation and plants. One square metre of modules holds up to 49 plants in individual pockets. Each module incorporates a drip-line irrigation system, modules can be fitted to both flat and curved surfaces. Weighing of the fully planted and saturated system is less than 40 kg per square metre, without plants - 2.1 kg. The water irrigation cycles can be installed with a fresh water top-up or the tank can be filled manually. The system is designed for rapid installation by a small team, minimizing on-site disruption [34]. Scotscape modular green wall system is given below (Figure 5).

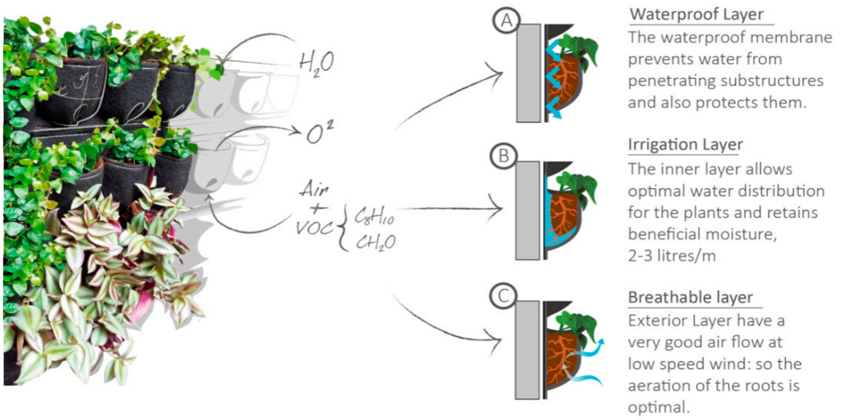


Figure 5. The modules of Scotscape modular green wall system.

The three most popular on the market vertical greening systems and one system, developed by the authors were investigated. The quantitative analysis of the plants, fitted into each modular green wall system is given below (Table 1).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 August 2023 doi:10.20944/preprints202308.0809.v1

Table 1. The quantitative analysis of plants fit into each MGWS.

MGWS / parameters	Grooflab	Biotecture	Vertis	Scotscape
Module dimensions, mm^2	300 x 300	600 x 450	760 x 590	1000 x 1000
Quantity of plants in standart module	5	16	14	49
Quantity of plants, per 1 m^2	45	60	32	49

A comprehensive analysis of all modular green wall system according to several criteria, the most important for choosing a system, we showed in the Table 2.

Table 2. The comprehensive analysis of all MGWS.

Modular green wall system / criterion for comparison	Grooflab	Biotecture	Vertis	Scotscape
Growing medium	Soil	Mineral wool	Pozzolan, crushed clay balls, peat	Fytotextile
Watering system	Manually or automatically, by pipework	Automatic	Automatic	Manually or automatically, by pipework
Changing the design	Rearranging modules	Rearranging modules	Rearranging modules	No, only dismantle
Square	1 m2	1 m2	1 m2	1 m2
Number of plants per 1 m^2	45	60	32	49
System weight	30 kg/ m^2	70 kg/ m^2	93,3 kg/ m^2	40 kg/ m^2

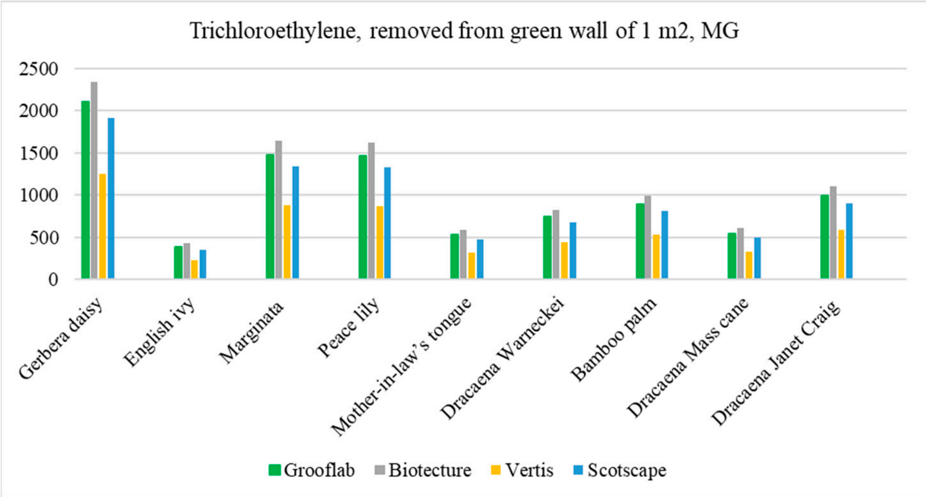
Analyzing Tables 1–2, we chose the best system from the presented sample. According to the criteria of weight, variability of the irrigation system, the ability to change the design - according to three of the 5 criteria, the best system is Grooflab. It should also be noted that the modules of this system can accommodate up to 45 plants per square meter, which is also quite a lot compared to competitors.

3. Results and Discussion

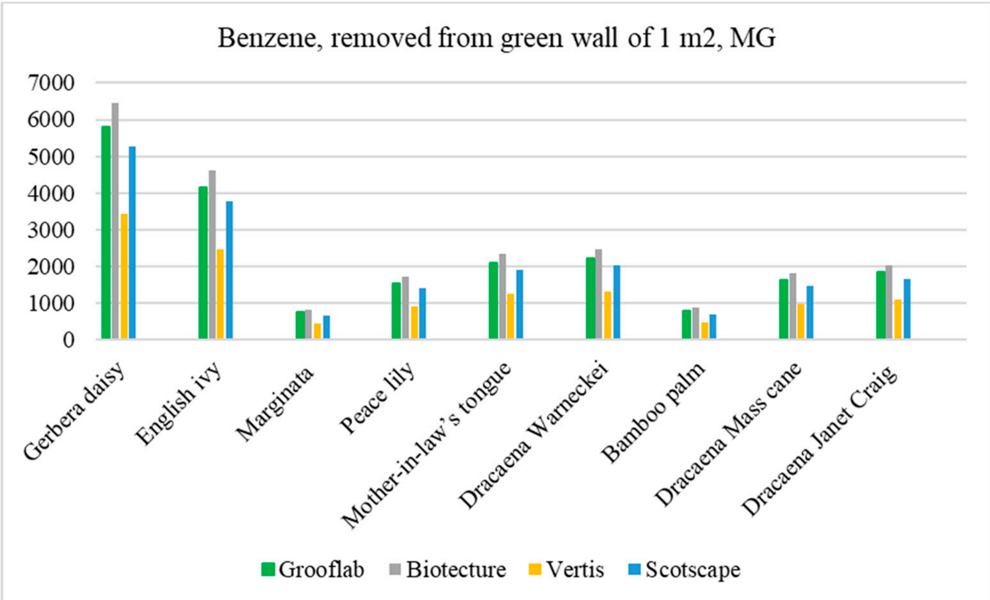
In this research we used the data of report of NASA [22] on the absorption of pollutants - benzene, formaldehyde, trichloroethylene, by different plants for a 24-hour exposure period in the Plexiglas chamber. We combined these data and get an approximate value of absorbed micrograms of three air pollutants in different modular green wall systems.

It is shown the calculations of three air pollutants removed in different modular green wall systems in figures below (Figure 6 a–c).

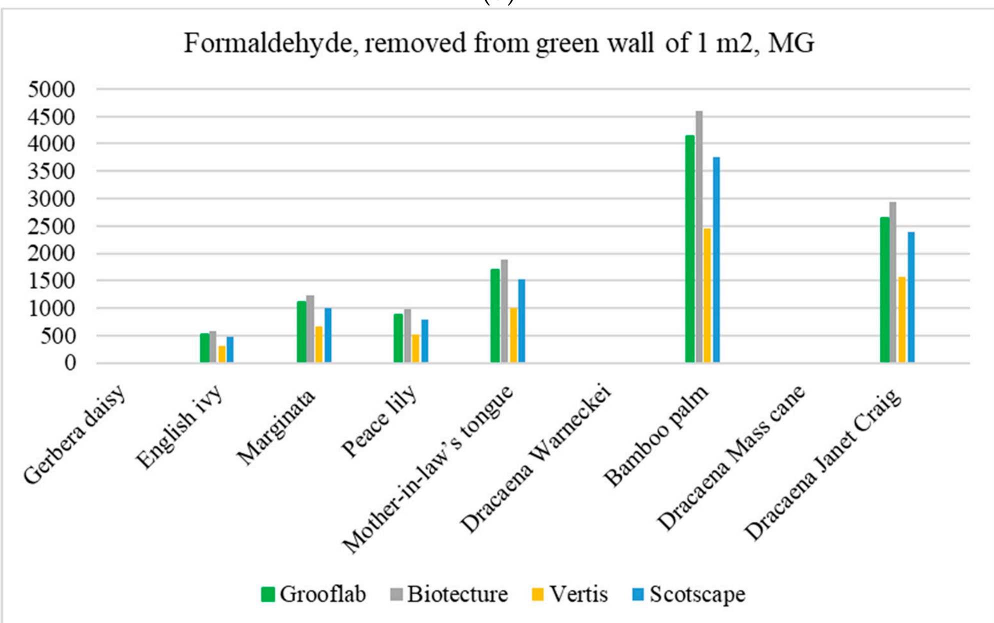
Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 10 August 2023 doi:10.20944/preprints202308.0809.v1



(**a**)



(**b**)



(**c**)

Figure 6. Diagrams of reducing the harmful air pollutants from different modular green wall systems: (**a**) TCE, (**b**) benzene, (**c**) formaldehyde.

Based on the comparison and evaluation of all three comparative diagrams presented, it can be concluded that the Grooflab and Biotecture modular green wall systems are the best in absorbing all three harmful substances from the atmosphere, when using all of the listed plants. In addition, it creates a specific handwriting style in architecture of green buildings (Figure 7).

Figure 7. Green building with using Grooflab modular system, patented by authors.

TSE is best absorbed by the following plants - 1. Gerbera daisy, 2. Marginata and Peace lily. Benzene is best absorbed by the following plants - 1. Gerbera daisy, 2. English ivy. Formaldehyde is best absorbed by the following plants - 1. Bamboo palm, 2. Dracaena Janet Craig. However, formaldehyde is not absorbed by Gerbera daisy at all, and Marginata and Peace lily, English ivy absorb it very little. Both Bamboo palm and Dracaena Janet Craig, to a small extent, in comparison with the presented plant analogues, also poorly absorb benzene and TSE.

Thus, when choosing a wall system, preference should be given to the best among analogues - Grooflab and Biotecture, and when using plants for such systems, combine 3-6 types of best air-purifying plants - 1. Gerbera daisy, 2. Bamboo palm, 3. Dracaena Janet Craig, 4. Marginata, 5. Peace lily and 6. English ivy.

4. Conclusions

Today, we know that biophilic architecture focuses more on the human experience of the built environment to improve well-being and productivity by connecting people with nature. Green wall plants reduce human stress, that was proved by idea of biophilia.

In the "age of consumption" and uncontrolled use of natural resources, the role of man in the conservation of nature and, in general, life on Earth is especially important for future generations.

We must very competently and rationally, and only if necessary, using the natural resources of our Green Planet, which are depleted hourly, including through the fault of man. We can reduce the maximum allowable human intervention in ecosystems, and at the same time help restore green spaces both in the natural environment - by planting trees, and in the urban environment, using greenery systems on buildings. And the role of plants in this case is to help us preserve nature.

Modular green wall systems for buildings are an advanced modern solution and a unique handwriting style in architecture of green buildings, the easiest way to help us get closer to nature and feel like a part of it.

We have found experimentally that systems - Grooflab and Biotecture are most effective modular green wall systems, with using plants - Gerbera daisy, Bamboo palm, Dracaena Janet Craig, Marginata, Peace lily and English ivy, and as a consequence – the more pollutants they can reduce.

While both approaches are important for creating sustainable and healthy buildings, biophilic architecture places more emphasis on the psychological and emotional benefits of connecting with nature. And, of course, we all need to create spaces that are not only beautiful and functional but also promote health and happiness for our future generations!

Author Contributions: This study was written by N.S. and E.K. The authors proposed the comparative analysis of different modular green wall systems. E.K. and N.S. planned and performed the experiment for green wall systems measurements. The manuscript was written by N.S., E.K. commented on by all authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: All authors declare no conflict of interest about the representation or interpretation of reported research results.

References

1. Zhong, W., Schroeder, T., Bekkering, J. Designing with nature: Advancing three-dimensional green spaces in architecture through frameworks for biophilic design and sustainability. *Frontiers of Architectural Research*. **2023**, 2095-2635, https://doi.org/10.1016/j.foar.2023.03.001
2. Ruixue Zhang, Yuyan Tang, Yuanxin Zhang, Zeyu Wang, Collaborative relationship discovery in green building technology innovation: Evidence from patents in China's construction industry, Journal of Cleaner Production, Volume 391,2023,136041, https://doi.org/10.1016/j.jclepro.2023.136041
3. Jianhua Yin, Changchun Li, Data governance and green technological innovation performance: A curvilinear relationship, Journal of Cleaner Production, Volume 379, Part 1,2022,134441, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2022.134441
4. Du, Qiang, Lu, Xinran, Li, Yi, Wu, Min, Bai, Libiao, Yu, Ming. Carbon Emissions in China's Construction Industry: Calculations, Factors and Regions, International Journal of Environmental Research and Public Health. Vol. 15, DO - 10.3390/ijerph15061220
5. Sang-Jin Ahn, Ho Young Yoon, 'Green chasm' in clean-tech for air pollution: Patent evidence of a long innovation cycle and a technological level gap, Journal of Cleaner Production, Volume 272,2020,122726, https://doi.org/10.1016/j.jclepro.2020.122726
6. Yang Han, Jechan Lee, Gu Haiping, Ki-Hyun Kim, Peng Wanxi, Neha Bhardwaj, Jong-Min Oh, Richard J.C. Brown. Plant-based remediation of air pollution: A review. Journal of Environmental Management, Volume 301, 2022, 113860, https://doi.org/10.1016/j.jenvman.2021.113860.
7. Michael D. Flowers, Edwin L. Fiscus, Kent O. Burkey, Fitzgerald L. Booker, Jean-Jacques B. Dubois, Photosynthesis, chlorophyll fluorescence, and yield of snap bean (Phaseolus vulgaris L.) genotypes differing in sensitivity to ozone, Environmental and Experimental Botany, Volume 61, Issue 2, 2007, Pages 190-198, https://doi.org/10.1016/j.envexpbot.2007.05.009.
8. Elisabetta Gravano, Valentina Giulietti, Rosanna Desotgiu, Filippo Bussotti, Paolo Grossoni, Giacomo Gerosa, Corrado Tani, Foliar response of an Ailanthus altissima clone in two sites with different levels of ozone-pollution, Environmental Pollution, Volume 121, Issue 1, 2003, Pages 137-146, https://doi.org/10.1016/S0269-7491(02)00180-X
9. Naomi J. Paull, Daniel Krix, Peter J. Irga, Fraser R. Torpy, Green wall plant tolerance to ambient urban air pollution, Urban Forestry & Urban Greening, Volume 63, 2021,127201, https://doi.org/10.1016/j.ufug.2021.127201.
10. Matteo De Lucia, Anna Treves, Elena Comino, Rice husk and thermal comfort: Design and evaluation of indoor modular green walls, Developments in the Built Environment, Volume 6, 2021, 100043, https://doi.org/10.1016/j.dibe.2021.100043.
11. Escolà-Gascón, Álex & Dagnall, Neil & Denovan, Andrew & Alsina-Pagès, Rosa & Freixes, Marc. (2023). Evidence of environmental urban design parameters that increase and reduce sense of place in Barcelona (Spain). Landscape and Urban Planning. 235. 104740. 10.1016/j.landurbplan.2023.104740.
12. K. Gunawardena, K. Steemers, Living walls in indoor environments, Build. Environ., 148 (2019), pp. 478-487, 10.1016/j.buildenv.2018.11.014
13. L. Yi, R. Liangliang, Z. Chunyan. Application analysis on thermal insulation of building surface greening-based on U-wert simulation. Proc. - 2019 Int. Conf. Smart Grid Electr. Autom. ICSGEA (2019), pp. 2019 63-67, 10.1109/ICSGEA.2019.00023
14. Sathya Bandaranayake Tharika Kahandawa Arachchi Kumari Gamage, Comparative Study to Assess the Thermal Behaviour of Sandwich Roof Panels with Coconut Fibre as an Alternative Core Material to Polyurethane, Electronic Journal of Structural Engineering, Vol 23, DOI- 10.56748/ejse.234153

15. Bevilacqua, P. (2021). The effectiveness of green roofs in reducing building energy consumptions across different climates. A summary of literature results. Renewable and Sustainable Energy Reviews, 151, 111523.
16. Bevilacqua, P., Bruno, R., & Arcuri, N. (2020). Green roofs in a Mediterranean climate: Energy performances based on in-situ experimental data. Renewable Energy, 152, 1414-1430.
17. Htet, Arkar & Liana, Sui & Aung, Theingi & Bhaumik, Amiya. (2023). Smart Buildings in the Age of Internet Technology: Civil Engineering's Role in Shaping an Energy-Efficient Future. Journal of Technology Innovations and Energy. 2. 8-19. 10.56556/jtie.v2i2.535.
18. Kasumu, Rebecca Oluwayimika & Oluwayimika. Senior secondary school students' perception of smart classroom: attitude and challenges, International Journal of Trendy Research in Engineering and Technology, 2023, Volume 7, Issue 3, pp.1-15
19. May Tzuc, Oscar & Jiménez Torres, Mario & Cruz, Andrea & Canul Turriza, Román Alejandro & Andrade-Durán, Juan & Pat, Felipe. (2023). Feasibility of the adaptive thermal comfort model under warm sub-humid climate conditions: cooling energy savings in campeche, Mexico. 13. 120. 10.22320/07190700.2023.13.01.10.
20. May Tzuc, Oscar & Hernández-Pérez, Iván & Castro, Karla Maria & Jiménez Torres, Mario & Castillo-Téllez, M & López, N. (2022). Modeling the effect of roof coatings materials on the building thermal temperature variations based on an artificial intelligence. Journal of Physics: Conference Series. 2180. 012014. 10.1088/1742-6596/2180/1/012014.
21. Tang, K.H.D., 2023. Green Walls as Mitigation of Urban Air Pollution: A Review of Their Effectiveness. Research in Ecology. 5(2): 1-13. DOI: https://doi.org/10.30564/re.v5i2.5710
22. Kasim, Rezzan. (2017). Using of Potted Ornamental Plants to Clean up Volatile Organic Compound that Cause Air Pollution Indoor. I. International Congress on Medicinal and Aromatic Plants
23. Roy, Misha & Shamim, F & Das, A. (2018). Indoor air pollution: sources, health impacts and control. 13. 75-82.
24. Wallace, L., E. Pellizzari, T. Hartwell, M. Rosenweig, M. Erickson, C. Sparacino, and H. Zelon. 1984. Personal exposureto volatile organic compounds: I. direct measurement in breathing-zone air, drinking water, food and exhaled breath. Env. Res. 35:193-211.
25. Pellizzari, E., T. Hartwell, C. Sparacino, C. Shelson, R. Whitmore, C. Leininger, and H. Zelon. 1984. Total Exposure Assessment Methodology (TEAM) Study: First Season, Northern New Jersey--Interim Report. Contract No. 68-02-3679. Washington: U.S. EPA.
26. Shushunova, N.; Korol, E.; Luzay, E.; Shafieva, D.; Bevilacqua, P. Ensuring the Safety of Buildings by Reducing the Noise Impact through the Use of Green Wall Systems. Energies 2022, 15, 8097. https://doi.org/10.3390/en15218097
27. Wolverton, B. C., Johnson, A., & Bounds, K. (1989). Interior landscape plants for indoor air pollution abatement (No. NASA-TM-101766).
28. Wolverton, B.C., and R.C. McDonald-McCaleb. 1986. Biotransformation of priority pollutants using biofilms and vascular plants. J. Miss. Acad. Sci., 31:79-89.
29. Marc Ottelé, Katia Perini, A.L.A. Fraaij, E.M. Haas, R. Raiteri, Comparative life cycle analysis for green façades and living wall systems, Energy and Buildings, Volume 43, Issue 12, 2011, Pages 3419-3429, ISSN 0378-7788,https://doi.org/10.1016/j.enbuild.2011.09.010
30. Ottelé, M. (2011). The green building envelope. Vertical Greening, Delft.
31. Bruno, Roberto & Ferraro, Vittorio & Bevilacqua, Piero & Settino, Jessica & Rollo, Antonino. (2023). Experimental tests to assess the effects of Phase Change Materials in building envelopes. 168-172. 10.1109/MetroLivEnv56897.2023.10164031.
32. https://www.biotecture.uk.com/content/uploads/External_Cladding_Living_Walls_and_Fire_Safety_Best_Practice_Guide.pdf
33. https://www.vertiss.net/vertiss-plus-le-module-vegetalise?lang=en
34. https://www.scotscape.co.uk/thank-you-document-download