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Application of Biophilic Installations for Indoor Air Quality Improvement

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1. Introduction

The progress of civilization forced a change in the human behavior and activity, which translated into the increased period of time spent indoors during the day by the inhabitants of developed countries. The available scientific data indicate that people stay in the space of the indoor environment for 85-90% of the day, or 19-21 hours. This time is devoted to studying, professional, social and home responsibilities, entertainment, exercise and rest (Godish 2001). Due to the progressive degradation of the natural environment, including air pollution in large urban centers, many residents intentionally avoid staying outdoors for extended periods of time. It is therefore obvious that people expect to have a safe indoor environment around them, as well as comfortable conditions for learning and working. Unfortunately, this comfort is often understood by designers, builders and architects as ensuring the proper indoor temperature and limiting the escape of heat. Ensuring proper air quality is hardly remembered.

The results of numerous international studies indicate a strong influence of the indoor air quality on health, well-being as well as the work efficiency and academic achievements (van den Bogerd et al. 2020, Luengas et al. 2015, Midouhas et al. 2018, Mujan et. al 2019). Poor air quality is responsible for numerous diseases of the upper and lower respiratory tract, headaches, rhinitis, allergies and skin changes. Prolonged exposure to airborne carcinogens may result in increased cancer incidence (passive smoking) (Stamatelopoulou et al. 2019). The most well-known phenomenon associated with improper air quality is the so-called sick building syndrome. Importantly, after leaving the sick building, the discomfort disappears (Pluschke & Schleibinger 2018). Therefore, it is reasonable to search for the techniques that ensure the removal of pollutants from indoor air and at the same time allow obtaining acceptable quality with least financial outlay. Such solutions include, among others biophilic installations (green walls) (Söderlund & Newman 2015).

Biophilia is the innate desire for humans to be in touch with nature through surroundings. This is represented in the built environment through the use of natural finishes, indoor plants and references to nature or its symmetry; all of which create a closer interaction with nature (Alhorr et al. 2016) Nowadays, in the modern workplaces, office, hospitals and commercial buildings, biophilia is becoming an important consideration for any interior design focused on the well-being of staff (Reeve et al. 2017). More and more attention is also paid to the aspect of using biophilic installations to purify indoor air. Although this movement has become a standard in many places around the world, it is yet to reach similar popularity in Poland.

The objective of this paper is to show the possibilities and limitations in using green wall structures to improve the indoor air quality.

2. Indoor air quality

The levels of indoor air pollutants are often a few times higher and much more concentrated than outdoors (Fleck et al. 2020). This is the result of outdoor air pollution and tightness of currently constructed buildings due to their energy saving requirements (Massey et al. 2016). The contaminants present in the indoor air can originate from the stream of infiltrating outdoor air, i.e.: polycyclic aromatic hydrocarbons (PAHs) and heavy metals sorbed on particulate matter (PM) and tropospheric ozone (O_3). Indoor pollutants can also come from typically endogenous sources as emissions of volatile organic compounds (VOCs) from interior furnishings – textiles, appliances, building materials, furniture; cleaning products (Dudzińska et al. 2010), and in the case of nitrogen oxides (NO_x) – from cooking. In turn, the main source of biological bioaerosol and carbon dioxide are the users themselves (Hospodosky et al. 2012). Additionally, the indoor air quality is affected by smoking in rooms, the use of household chemicals and the cleanliness of the ventilation system (Dela Cruz et al. 2014). Some chemical compounds present in the indoor environment in a gas phase (terpenes) or combined with dust particles (polybrominated diphenyl ethers) are susceptible to undergoing chemical transformations under the influence of light or oxidants. The products of these reactions show higher toxicity than the parent compounds (Staszowska 2017, Wolkoff 2020). Although not normally regarded as toxic, at elevated (>1000 ppm) concentrations CO_2 can cause adverse health effects relating to the mucous membranes (dry eyes, sore throat, sneezing) and the lower respiratory tract (tight chest, short breath, cough). An increase in the CO_2 concentration above the recommended values is manifested by drowsiness and fatigue of users (Godish 2001).

In most modern buildings, the air quality is unsatisfactory and needs improvement. It can be obtained by implementing the following solutions. Firstly, low emission building materials should be used in construction and furnishing. The second recommended action is to increase the air exchange rate to refresh the indoor air and dilute contaminants. The costs of such action are problematic, as maintaining mechanical ventilation or air conditioning systems requires significant financial outlays. The last tool to improve the indoor air quality is to use the purification techniques (Guieysse et al. 2008). They focus on removing contaminants from the air, or masking their presence or mitigating its effects. The indoor air can be purified using conventional techniques (filtration, sorption on activated carbon, ionization) as well as unconventional solutions, which include photocatalysis and phytoremediation (Luengas et al. 2015).

3. Application of plants for indoor air purification

Greenery can affect various aspects of life, some can relieve and reduce stress, while others stimulate cognitive functions, creativity and commitment (Alcock et al. 2014, Chen et al. 2020, Yin et al. 2018). The universal intention of biophilic design is healing, both for people and the surrounding space. Moreover, the studies conducted over the last few decades have demonstrated that potted plants can reduce the concentrations of most types of indoor air pollutants (Table 1) (Darlington et al. 2010, Kim et al. 2018).

Plants are capable of depositing and assimilating a wide group of gaseous pollutants and dusts present in the air. Due to the subject of this study, only those pollutants that have the greatest impact on the indoor air quality will be discussed. Ornamental plants, owing to the secreted phytoncides, are able to inhibit the growth of harmful microorganisms in their environment (Pettit et al. 2018). They can also purify the air, because they show high tolerance to a wide range of inorganic and organic pollutants. This is confirmed by the results of the studies conducted under model laboratory test-chamber conditions since the beginning of the 1980s (Irga et al. 2018). However, the mechanism of phytoremediation of indoor air pollutants has still not been fully explained. It is believed that both the aboveground parts (leaves, stems) and the root zone of decorative plants have the ability to remove various groups of chemical substances and the effectiveness of this process depends on the species of the plant, lighting conditions, ambient temperature, type and humidity of the growing medium, as well as lipophilicity of the removed impurity (Darlington et al. 2010, Dela Cruz et al. 2014). Initially, ornamental house plants were tested. Currently, the subject of research are mainly modular biophilic installations called *green walls*, which form both vascular plant species, as well as bryophytes, mosses, liverworts and gills (Irga et al. 2018).

Table 1. Recommended indoor air purifying ornamental potted plants

Plant name	Botanical name	Pollutants removed
Devil's ivy	*Epipremnum aureum*	xylene, benzene, formaldehyde, trichloroethylene
Dwarf date palm	*Phoenix roebelenii*	formaldehyd, xylene
Peace lilies	*Spathiphyllum spp.*	benzene, carbon monoxide, formaldehyde, trichloroethylene, xylene, acetone
Heartleaf philodendron	*Philodendron scandes*	formaldehyde
Spider plant	*Chlorophytum comosum*	formaldehyde, xylene
Florist's daisy	*Chrysanthemum morifolium*	ammonia, benzene, formaldehyde, xylene
Rubber plant	*Ficus elastic*	xylene, benzene, formaldehyde, trichloroethylene
Boston fern	*Nephrolepis exaltata*	formaldehyde and xylene
Areca palm	*Chrysalidocarpus lutescens*	benzene, carbon monoxide, formaldehyde, trichloroethylene, xylene
Pineapple plant	*Ananas comosus*	CO_2
Dracaena fragrans	*Dracaena deremensis*	xylene, trichloroethylene, formaldehyde
Snake plant/ Mother-in-law's tongue	*Sansevieria trifasciata*	formaldehyde, trichloroethylene, benzene, xylene
Aloe vera	*Aloe vera*	formaldehyde
English ivy	*Hedera helix*	formaldehyde, benzene
Flamingo lily/Fleur	*Anthurium andraeanum*	formaldehyde, ammonia, xylene, toluene
Lady palm	*Rhapis excelsa*	formaldehyde, ammonia, xylene
Bamboo palm	*Chamaedorea seifrizii*	formaldehyde, trichloroethylene, benzene

Toxic volatile organic compounds, e.g. formaldehyde, benzene, toluene, and xylenes, after penetration through stomata can be accumulated in tissues in an unchanged form, metabolized and incorporated into cellular structures or undergo biotransformation with the participation of microorganisms inhabiting the phyllosphere and rhizosphere. The absorption of VOCs by substrate particles has also been reported. In most cases of the tested ornamental plant species, the effectiveness of VOCs air purification increased along with the concentration of pollutants in the air and was best carried out under the daytime conditions. Even a long-term exposure of plants to high VOC concentrations did not inhibit their growth (Dela Cruz et sl. 2014, Fujii et al. 2005, Kim et al. 2018, Soreanu et al. 2013).

Ozone, which can come from infiltration as well as in situ, is removed mainly through stomata. The speed of the process depends on the plant species

(Abbass et al. 2017). In the case of particulate matter, the effectiveness of their removal by plants is proportional to the mixing of the aerodynamic diameter of dusts and constitutes a passive process. The mechanism itself has not been fully understood. The key role is played by waxes, which cover the leaf blades. In addition to dry PM deposition on the leaf surface, the reactions between dust components, e.g. hydrophobic PAHs, electrostatic interactions of adsorbed heavy metals and waxes cannot be excluded. It is also possible to use the PM components for plant metabolism (Gawrońska & Bakera 2015, Peng et al. 2020, Petitt et al. 2017).

The issue of the effectiveness of plants in removing the excess carbon dioxide from indoor air is still debatable. Some researchers claim that the CO_2 assimilation is rather small (Gubb et al. 2018), while others, on the contrary, believe that they reduce the ventilation costs (Tudiwer & Korjenic 2017). Torpy et al. (2014) indicates that the rate of CO_2 removal from the air by the tested plants depends on the species and lighting conditions (intensity and time).

The presence of indoor plants has a positive effect on the regulation of relative humidity (RH), which is particularly beneficial during the heating period. At the same time, the growth of RH by plants does not generate the conditions for the development of mold fungi, even in very airtight rooms (Tudiwer & Korjenic 2017, Irga et al. 2017, Fleck et al. 2020).

What is known for sure is that the potted plants alone are unable to remove enough pollutants to improve the indoor air quality in commercial buildings. Studies have now moved onto green walls (living walls, indoor vertical gardens) which boast a higher density of plants and increased the purifying properties (Fig. 1 and Fig. 2).

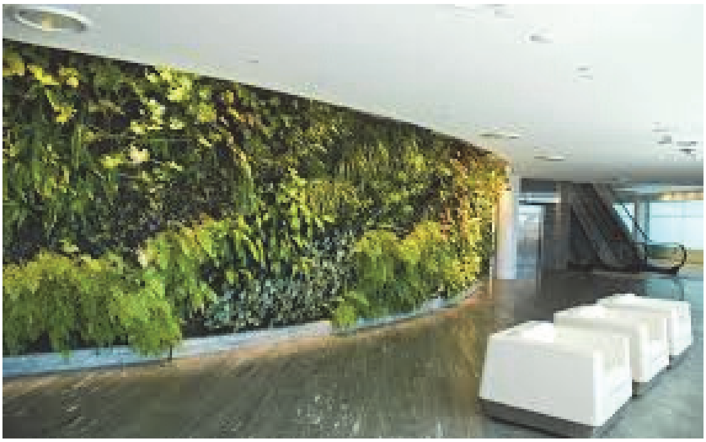

Fig. 1. Living wall in building lobby (www.asiagreenbuildings.com)

In terms of construction, three types of biophilic installations can be distinguished. The first one is usually a group of several or a dozen popular potted plants, the arrangement of which in the room is free and is mainly due to the aesthetic reasons. The second and third types are called passive and active vertical green walls. Their construction is almost identical to that of external green wall systems found on facades and balconies of buildings. They are modular systems (trays, vessels, planter tiles and flexible bags) filled with plants of various species or being a monoculture. The main difference between passive and active green walls is the way how air is circulated within the structure itself. Active indoor green installations represent the technical advancement that enhances the air purifying services further by actively forcing air through a bio-wall filter with the use of air fans (Gunawardena & Steemers 2019).

Indoor living green walls include a vertically applied growth medium such as soil, substitute substrate, or hydroculture felt; as well as an integrated hydration and fertigation delivery system. Indoor green walls are often constructed of modular panels that hold a growing medium and can be categorized according to the type of growth media used: mat media, and structural media. The mat type systems tend to be either coir fiber or felt mats. The mat media are quite thin, even in multiple layers, and as such cannot support extensive root systems of mature plants for more than three to five years before the roots overtake the mat and water is not able to adequately wick through the mats. The method of repairing these systems is to replace large sections of the system at a time by cutting the mat out of the wall and replacing it with a new one. This process compromises the root structures of the neighboring plants on the wall and often kills many surrounding plants in the reparation process (Clapp & Klotz 2018, Moya et al. 2019).

The most popular are semi-open cell polyurethane sheet media utilizing an egg crate pattern, which have been successfully used for vertical walls in recent years (Fig. 2).

Fig. 2. Installation of green wall (www.gardenspot.pl)

The water holding capacity of these engineered polyurethanes vastly exceeds that of coir and felt based systems. Polyurethanes do not biodegrade, and hence stay viable as an active substrate for 20+ years. The vertical wall systems utilizing polyurethane sheeting typically employ a sandwich construction where a water proof membrane is applied to the back, the polyurethane sheeting (typically two sheets with irrigation lines in between) is laid and then a mesh or anchor braces/bars secure the assembly to the wall. Pockets are cut into the face of the first urethane sheet into which plants are inserted. Soil is typically removed from the roots of any plants prior to insertion into the urethane mattress substrate. A flaked or chopped noodle version of the same polyurethane material can also be added to the existing structural media mixes to boost water retention (Riley 2017).

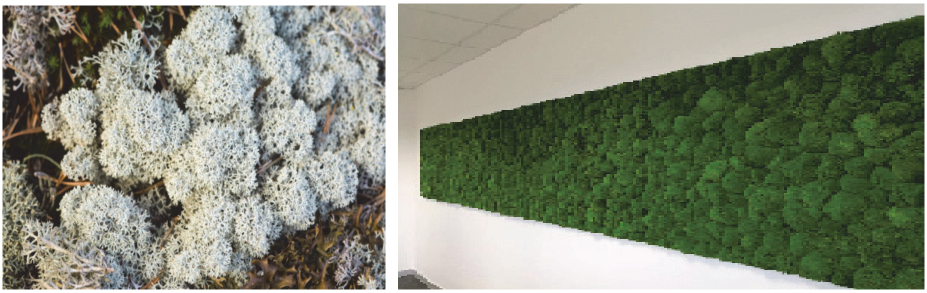

Fig. 3. Reindeer lichen in nature (on the left) and as an interior green wall (on the right)

Essentially, a collection of potted plants in the individual soil-cells are subject to the same changes that are faced by most houseplants: soil compaction, climatic stress, and soil nutrient replenishment (Egea et al. 2014). It is worth emphasizing that currently the role of HVAQ system engineers in the process of selecting specific plant species for green wall indoor modules is marginal. Still, interior architects, in consultation with florists, decide on the species composition of biophilic installations. Thus, when creating modules and plant compositions, the most important are aesthetic issues, not practical use of greenery to improve the air quality.

4. Indoor biophilic installations – limitations of use

Despite many studies, the accuracy of results extrapolating from chamber experiments to real-world conditions is questionable. While the issues of designing the structure and arrangement of green wall systems (for aesthetic purposes) in indoor spaces have been developed very well, there are still no clear guidelines or recommendations regarding the employment of plants as indoor air purification systems. Just saying that plants are able to remove pollution from the air and improve the indoor climate is not enough if the problem is to be approached in a practical way. The obstacles to the wider use of biophilic installations as an indoor air purifier are the following issues:

- no clear data on how many plants of a given species should be used in the module to achieve an effective level of pollution reduction,
- what lighting conditions should be used for the plants of a given species,
- how to combine the functioning of green walls and HVAC systems,
- how to estimate the potential ventilation equivalence of the tested plants,
- how to control the operation of a biophilic installation under changing internal conditions.

5. Conclusions

While phytoremediation is a recognized way of air purification, the issue of its effectiveness under real conditions remains debatable. The challenges that this technique will face in the near future include: genetic modification of plants dedicated to individual pollutant, testing new substrates, fertilization and irrigation systems as well as systems for remote monitoring of the condition of installations. They will allow developing the guidelines and recommendations for ventilation engineers and interior architects. However, it should be remembered that biophilic installations, with the current state of knowledge, can be a support, rather than an alternative to the traditional air purification techniques. Hence, it cannot be expected that their pollutants removal efficiency will be as high as that of conventional mechanical systems.

References

Abbas, O.A., Sailor, D.J., Gall, E.T. (2017). Effectiveness of indoor plants for passive removal of indoor ozone. *Building and Environment, 119*, 62-70.

Alcock, I., White, M.P., Wheeler, B.W., Fleming, L.E., Depledge, M.H. (2014). Longitudinal effects on mental health of moving to greener and less green urban area. *Environmental Science & Technology*, *48*(2), 1247-1255.

Alhorr, Y., Aarif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., Elsarrag, E. (2016). Occupant productivity and office indoor environment quality: a review of the literature. *Building and Environment, 105*, 369-389.

Chen, R.Y., Ho, K.F., Hong, G.B., Chuang, K.J. (2020). Houseplant, indoor air pollution, and cardiovascular effects among elderly subjects in Taipei, Taiwan. *Science of the Total Environment, 705*, 135770.

Clapp, L., Klotz, H. (2017). *Vertical gardens*. London, Sydney, Auckland, New Holland Publishers.

Darlington, A., Chan, M., Malloch, D., Pilger, C., Dixon, M.A. (2010). The biofiltration of indoor air: implications for air quality. *Indoor Air, 21*, 39-46.

Dela Cruz, M., Christensen, J.H., Thomsen, J.D., Muller, R. (2014). Can ornament potted plants remove volatile organic compounds from indoor air? – a review. *Environmental Science and Pollution Research, 21*, 13909-13928.

Dudzińska, M.D., Staszowska, A., Połednik, B. (2010). Preliminary study of effect of furniture and finishing materials on formaldehyde concentration in office rooms. *Environmental Protection Engineering*, *35*, 225-233.

Egea, G., Pérez-Urrestarazu, L., González-Pérez, J., Franco-Salas, A., Fernández-Cañero, R. (2014). Lighting systems evaluation for indoor living walls. *Urban Forestry & Greening, 13*, 475-483.

Fleck, R., Gill, R.L., Pettit, T., Irga, P.J., Williams, N.L.R., Seymour, J.R., Torpy, F.R. (2020). Characterisation of fungal and bacterial dynamics in an active green wall used for indoor air pollutant removal. *Building and Environment, 179,* 106987.

Fujii, S., Ch, H., Kagi, N., Miyamura, H., Kiim, Y.S. (2005). Effects on air pollutant removal by plant absorption and adsorption. B*uilding and Environment, 40*, 105-112.

Gawrońska, H., Bakera, B. (2015). Phytoremediation of particulate matter from indoor air by *Chlorophytum comosum L.* plants. *Air Quality, Atmosphere & Health*, *8,* 265-272.

Godish, T. (2001). *Indoor environmental quality.* CRC Press.

Gubb, C., Blanusa, T., Griffiths, A., Pfrang, C. (2018). Can houseplants improve indoor air quality by removing CO_2 and increasing relative humidity? *Air Quality, Atmosphere & Health*, *11*, 1191-1201.

Gubb C., Blanusa T., Griffiths A., Pfrang C. (2020). Can plants be considered a building service? *Building Services Engineering Research & Technology, 41*(3), 374-384.

Guieysse, B., Hort, C., Platel, V., Munoz, R., Ondarts, M., Revah, S. (2008). Biological treatment of indoor air for VOC removal: potential and challenges. *Biotechnology Advances, 26,* 398-410.

Gunawardena K., Steemers K. (2019). Living walls in indoor environments. *Building and Environment, 148*, 478-487.

Horr, Y.A., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., Elsarrag, E. (2016). Occupant productivity and office indoor environment quality: a review of the literature. *Building and Environment,105,* 369-389.

Hospodosky, D., Qian, J., Nazaroff, W.W., Yamamoto, N., Bibby, K., Rismani-Yazdi, H. Peccia, J. (2012). Human occupancy as a source of indoo airborne bacteria. *PLos ONE, 7*(4)*,* e34867.

Irga, P., Abdo, P., Zavattaro, M., Torpy, F.R. (2017). An assessment of the potential fungal bioaerosol production from an active living wall. *Building and Environment, 111*, 140-146.

Irga, P.J., Pettit, T.J., Torpy, F.R. (2018). The phytoremediation in indoor air pollution: a review on the technology development from the potted plant through to functional green wall biofilters. *Reviews of Environmental Science Biotechnology, 17,* 395-415.

Kim, K.J., Khalekuzzaman, M., Suh, J.N., Kim,, H.J., Shagol, S., Kim, H.H. (2018). Phytoremediation of volatile organic compounds by indoor plants. *Horticulture, Environment, and Biotechnology*, *59*, 143-157.

Luengas, A., Barona, A., Hort, C. (2015). A review of indoor air treatment technologies. *Reviews in Environmental Science and Biotechnology, 14*, 499-522.

Massey, D.D., Habil, M., Taneja, A. (2016). Particles in different indoor microenvironments – its implications on occupants. *Building and Environment, 106,* 237-244.

Midouhas, E., Kokosi, T., Flouri, E. (2018). Outdoor and indoor air quality and cognitive ability in young children. *Environmental Research, 161,* 321-328.

Moya, T., van den Dobbelsteen, A., Ottele, M., Bluyssen, P.M. (2019). A review of green systems within the indoor environment. *Indoor and Built Environment, 28*(3), 298-309.

Mujan, I., Anđelković, A.S., Munćan, V., Kljapić, M., Ružić, D. (2019). Influence of indoor environmental quality on human health and productivity – a review. *Journal of Cleaner Productivity, 217*, 646-657.

Peng, Z., Deng, W., Hong, Y., Chen, Y. (2020). An experimental work to investigate the capabilities of plants to remove particulate matters in an enclosed greenhouse. *Air Quality, Atmosphere & Health*, *13,* 477-488.

Pettit, T., Irga, P.J., Abdo, P., Torpy, F.R. (2017). Do the plants in functional green walls contribute to their ability to filter particulate matter? *Building and Environment, 125*, 299-307.

Pettit, T., Irga, P.J., Torpy, F.R. (2018). Towards practical indoor air phytoremediation: a review. *Chemosphere, 208*, 960-974.

Pluschke, P., Schleibinger, H. (2018). *Indoor air pollution*. Springer.

Riley, B. (2017). The state of the art of living walls: lesson learned. *Building and Environment, 114,* 219-232.

Reeve, A., Nieberler-Walker, K., Desha, C. (2017). Healing gardens in children's hospitals: reflections on benefits, preferences and design from visitors' books. *Urban Forestry & Urban Greening, 26*, 48-56.

Soreanu, G., Dixon, M., Darlington A. (2013). Botanical biofiltration of indoor gaseous pollutants – a mini review. *Chemical Engineering Journal, 229*, 585-594.

Söderlund, J., Newman, P. (2015). Biophilic architecture: a review of the rationale and outcomes. *AIMS Environmental Science, 2*(4), 950-969.

Staszowska A. (2017). Photodegradation of lower polybrominated diphenyl ether congeners in indoor air – model studies. *Journal of Ecological Engineering 18*(3), 180-186.

Stamatelopoulou, A., Asimakopoulos, D.N., Maggos, T. (2019). Effects of PM, TVOCs and comfort parameters on indoor air quality of residences with young children. *Building and Environment, 150,* 233-244.

Torpy, F.R., Irga, P.J., Burchett, M.D. (2014). Profiling indoor plants for the amelioration of high CO_2 concentrations. *Urban Forestry & Urban Greening, 13*, 227-233.

Tudiwer, D., Korjenic, A. (2017). The effect of an indoor living wall system on humidity, mould spores and CO_2 concentration. *Energy and Buildings, 146*, 73-86.

Wolkoff, P. (2020). Indoor air chemistry: terpene reaction products and airway effects. *International Journal of Hygiene and Environmental Health, 225*, 113439.

van den Bogerd, N., Dijkstra, S.C., Tanja-Dijkstra, K., de Boer, M.R., Seidell, J.C., Koole, S.L., Maas, J. (2020). Greening the classroom: three field experiments on the effects of indoor nature on students' attention, well-being, and perceived environmental quality. *Building and Environment, 171,* 106675.

Yin, J., Zhu, S., MacNaughton, P., Allen, J.G., Spengler, J.D. (2018). Physiological and cognitive performance of exposure to biophilic indoor environment. *Building and Environment*, *132,* 255-262.

Abstract

This paper discusses the possibilities and limitations of using biophilic installations to improve the indoor air quality in residential and commercial spaces. Modular plant systems can provide the support or, in smaller facilities, even an alternative to the conventional indoor air purification techniques, such as filtration. The unquestionable advantage of green walls is their comprehensive influence on the indoor air quality by shaping both appropriate thermal and humidity conditions as well as the chemical air composition. However, these constructions are not mechanical systems and therefore, the effectiveness of these specific types of living air purifiers in removing gaseous pollutants and particulate matter cannot be expected to match the level of traditional systems.

Keywords:
indoor air quality, biophilic installation, phytoremediation, green walls

Wykorzystanie instalacji biofilicznych do poprawy jakości powietrza wewnętrznego

Streszczenie

W pracy omówiono możliwości i ograniczenia wykorzystania instalacji biofilicznych do poprawy jakości powietrza wewnętrznego w przestrzeniach mieszkalnych i komercyjnych. Roślinne systemy modułowe mogą stanowić wsparcie lub w mniejszych obiektach alternatywę dla konwencjonalnych technik oczyszczania powietrza wewnętrznego jakim jest filtracja. Niekwestionowaną zaletą zielonych ścian jest ich kompleksowy wpływ na jakość powietrza wewnętrznego poprzez kształtowanie zarówno odpowiednich warunków cieplno-wilgotnościowych jaki i składu chemicznego powietrza. Nie są to jednak układy mechaniczne i nie można oczekiwać, aby te swoistego rodzaju żywe oczyszczacze powietrza osiągały skuteczności w usuwaniu zanieczyszczeń gazowych i pyłowych na poziomie tradycyjnych systemów.

Słowa kluczowe:
jakość powietrza wewnętrznego, instalacje biofiliczne, fitoremediacja, zielone ściany