PROBLEMY EKOROZWOJU – PROBLEMS OF SUSTAINABLE DEVELOPMENT
2020, 15(2), 245-252
DOI: 10.35784/pe.2020.2.24

Air Purification in Sustainable Buildings

Oczyszczanie powietrza wewnętrznego w budynkach zrównoważonych

Amelia Staszowska

Department of Indoor and Outdoor Air Quality, Lublin University of Technology,
ul. Nadbystrzycka 40B, Lublin, Poland
E-mail: a.staszowska@pollub.pl
ORCID 0000-0002-7434-6480

Abstract

This paper concerns the issue of indoor air purification techniques in sustainable public buildings and the residential sector. One of the requirements of sustainable construction is to reduce the energy costs, minimize waste, improve the well-being of users and create green space. The most important certification systems for green (ecological) buildings such as LEED or BREEAM also include the assessment of the indoor environment in terms of the air quality, noise level, building acoustics and energy consumption. Traditional air treatment and purification systems require the use of numerous devices, air transport systems, which are energy-consuming. It is necessary to clean or replace the working elements periodically. The alternative is biophilic installations (green walls) based on the natural properties of plants for removing gaseous pollutants, particulate matter and even bioaerosols from the air. Plants improve humidity, regulate the carbon dioxide concentration, ionize the air and suppress noise. However, the processes of photocatalytic degradation of gaseous compounds are a very promising method of removing impurities, due to low costs, mild process conditions (temperature and pressure) and the possibility of complete mineralization of impurities.

Keywords: indoor air quality, sustainable buildings, phytoremediation, photocatlysis, innovative materials

Streszczenie

Praca dotyczy zagadnienia technik oczyszczania powietrza wewnętrznego w zrównoważonych budynkach użyteczności publicznej i sektorze mieszkalnym. Jednym z wymogów budownictwa zrównoważonego jest ograniczenie kosztów zużycia energii, minimalizacja powstawania odpadów, poprawa samopoczucia użytkowników oraz tworzenie zielonej przestrzeni. Najważniejsze systemy certyfikacji zielonych/ ekologicznych budynków takie jak LEED czy BREEAM obejmują również ocenę środowiska wewnętrznego w zakresie jakości powietrza, poziomu hałasu, akustyki budynku i jego energochłonności. Tradycyjne systemy uzdatniania i oczyszczania powietrza wymagają wykorzystania licznych urządzeń, systemów przesyłu powietrza świeżego i zużytego, które są energochłonne. Konieczne jest ich okresowe czyszczenie lub wymiana elementów roboczych. Alternatywą są instalacje biofiliczne (zielone ściany) oparte na naturalnych właściwościach roślin do usuwania z powietrza zanieczyszczeń gazowych, pyłów a nawet bioaerozoli. Rośliny poprawiają wilgotność, regulują stężenie dwutlenku węgla, jonizują powietrze i tłumią hałas.

Natomiast procesy fotokatalitycznej degradacji związków gazowych są bardzo obiecującą metodą usuwania zanieczyszczeń, ze względu na niewielkie koszty, łagodne warunki prowadzenia procesów (temperatura i ciśnienie) i możliwość całkowitej mineralizacji zanieczyszczeń.

Słowa kluczowe: jakość powietrza wewnętrznego, zrównoważone budownictwo, fitoremediacja, fotokataliza, materiały innowacyjne

1. Introduction

The rapid progress of civilization in recent decades has forced a change in the human behavior and activity, translated into the length of time spent indoors during the day by the inhabitants of developed countries (Pawłowski, 2011). The available scientific data indicate that people stay in the space of the indoor environment for 90% of the day. This time is devoted to studying, working, social and home responsibilities, entertainment, exercising and resting (Tham, 2016). 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 on the work efficiency and learning achievements (Kelly et al., 2019). Poor air quality is responsible for numerous diseases of the upper and lower respiratory tract, headaches, rhinitis, allergies and skin changes. Uncontrolled long term exposure to airborne mutagens may result in increased cancer incidence (passive smoking). The most well-known phenomenon associated with poor air quality is the so-called sick building syndrome (Kotzias et al., 2017).

It is estimated that the construction sector is currently responsible for 50% of global energy consumption during the year. This energy is used for heating, lighting and also for air treatment for ventilation and air-conditioning systems (HVAC). This energy comes mainly from the combustion of conventional fuels and significantly contributes to the global air pollution. Carbon dioxide and other greenhouse gases contained in flue gas have an impact on the intensification of the greenhouse effect phenomenon. In relation to the natural environment, construction is typically a consumer. Striving to stop further environmental degradation through the continuous increase of building structures is reflected in a change in the approach of designers and architects to the construction process. It is a pro-ecological direction in which the construction process is currently perceived on many levels, i.e. through the perspective of the building's life cycle from its erection, through use, periodic renovations to demolition (Bauer et al, 2010).

Sustainable construction enables to create such an internal space that ensures the required air quality, high standards of use and environmental friendliness at the same time.

Among Sustainable Development Goals, adopted by the UN in 2015, there are few which apply in the context of sustainable buildings. They are: Goal 3: Good health, Goal 9: Industry, innovation and infrastructure and Goal 11. Sustainable cities and communities. If energy is to be taken into account, Goal 7: Affordable and clean (renewable) energy, should also be considered (UN, 2015). The most important one is Good health, since living in an unhealthy environment will limit the possibilities of realizing all Sustainable Development Goals (UN, 2015). The aim of this work was to characterize the air quality improvement techniques that are used in sustainable buildings.

2. Sustainable architecture

Sustainable architecture is the use of the design strategies that help reduce the negative impact of buildings on the environment during their construction and, more importantly, long-term use. Such buildings are called green, ecological or sustainable (Bielniak et al., 2013). The sources of modern ecological construction should be seen in the assumptions of the policy of harmonious development of humanity in accordance with the principles of sustainable development. This idea is currently the widest formula defining the relationship of man and his activities with the natural environment.

According to the definition in the Brundtland Report (1988), the sustainable development should be understood as a way of managing an environment in which meeting the needs of the present generation will not reduce the ability of future generations to meet their needs. This means that the consumed resources should be compensated on an ongoing basis by introducing new resources of similar value and utility. This specific leveling of deficiencies or shortages of consumed natural resources in the appropriate time frame is difficult to implement in the case of the construction sector. Therefore, in the definition of the sustainable development adapted for the needs of ecological construction, it is acceptable to use a significant amount of raw materials as long as they are renewable or occur on Earth in inexhaustible quantities. Sand is an example of such raw material. Due to the rapid economic development of China and the Middle East countries and the gigantic construction investments carried out by these countries (the Three Gorges Dam, Dubai Palm Island complex), there is a real threat of shortage of this material (Marchwiński and Zielonka-Jung, 2014).

A certain amount of waste mass and pollution generated by building infrastructure is also acceptable, provided it does not exceed the planet's self-regulation level. Ultimately, it can be said that the concept of sustainable building is not the same as the assumption of its autonomy and self-sufficiency as required in the Brundtland Report (Firląg, 2018).

For many years, sustainable buildings have constituted a rather small share of the sector in relation to the buildings constructed using the traditional technologies. The main reason for this state of affairs should be seen in the high costs of building such facilities. Currently, sustainable buildings are gaining popularity because there are many beneficial sources of financing for this type of investment. The incentive includes numerous non-returnable funds that cover even the costs of the entire project.

The sustainable development assumptions can be implemented both in housing and, increasingly, in the public utilities sector. These are office buildings, cultural facilities, hotels, shopping malls and even religious facilities.

In order for a building to be sustainable, it should:

• be characterized by low demand for usable energy for heating and ventilation,
• use renewable energy sources,
• minimize waste production and maximize its reuse,
• ensure low water consumption and its recovery,
• use low-processed building and finishing materials,
• ensure creation of a space rich in greenery;
• improves the well-being of users by ensuring proper indoor air quality, lighting and acoustics (López et al., 2019).

3. Air purification techniques in the sustainable buildings

The indisputable fact is that the indoor air quality affects the health, well-being, work performance of room occupants and, in the case of children, also the rate of knowledge acquisition and cognitive skills (Midouhas et al., 2018). The issue of obtaining the right indoor air quality in sustainable buildings is complex because it is determined by three groups of factors of a physical, chemical and biological nature. The sources of chemical and biological pollution should be sought both in the external air, which is introduced into the building by natural or mechanical ventilation, as well as in the internal environment itself (Kotzias et al., 2017).

Along with the outside air, particulate matter with absorbed heavy metals, polycyclic aromatic hydrocarbons and other volatile organic compounds are inadvertently introduced into the buildings (Massey et al., 2016; Morawska et al., 2017). The infiltrating air is also a source of tropospheric ozone, nitrogen oxides and non-methane volatile organic compounds. In contrast, indoor activities like cleaning, cooking, smoking, the operation of HVAC systems, off-gassing from household products, paints, furnishing materials, and building materials are considered to be the main endogenous sources affecting the indoor air quality (Dudzińska et al., 2010). The most known group of chemical impurities in indoor air corresponds to volatile organic compounds (VOCs). These compounds include aliphatic and aromatic hydrocarbons, aldehydes and ketones. Some of them, such as benzene, toluene, ethylene, xylenes (BTEX) and formaldehyde, have been suggested to be possible carcinogens, mutagens and teratogens. Long-term exposure to VOCs can result in acute and chronic adverse health effects as eyes irritation, sensitization reaction of skin and respiratory tract, and neurological problems (WHO, 2010). In turn, the basic source of biological bioaerosol and carbon dioxide are the users themselves (Lunegas et al., 2015).

One of the main features of a sustainable building is its energy efficiency. Thermo-modernization ensures a reduction in the demand and heat consumption for heating while improving the thermal comfort of the building. As part of thermo-modernization, the most common solutions include: insulation of walls, roof, floors on the ground, replacement of window and door joinery, use of mechanical ventilation with the heat recovery and replacement of the heat source itself. However, such activities have a negative impact on the indoor air quality (Steinemann et al., 2017). The building becomes so tight that the natural supply of fresh air is stopped. The relative humidity of the air increases, which contributes to the biological growth of molds, fungi on building structural elements and can even lead to their destruction through biological corrosion (WHO, 2009). In the absence of a sufficient stream of fresh air, the gas and dust pollutants are concentrated. The consequences of this state of affairs are felt by users – often complaining about chronic health problems and permanent fatigue due to the concentration of carbon dioxide exceeding the recommended hygiene standard which is 1000 ppm (Lunegas et al., 2015).

By design, a sustainable building is to be environmentally friendly but also it has to fulfill this function in relation to its users. Appropriate comfort of staying in a room depends on: the quality of the internal air, internal temperatures, humidity, proper lighting, acoustic comfort, as well as elements of equipment.

Unfortunately, the air in most rooms needs cleaning. Several air purifying techniques are available on the market. The most popular are filtration, sorption, and ionization. Their disadvantage is often masking of pollution, rather than their elimination from the air. They also do not allow the emission control and often, e.g. air filters, are a source of secondary pollution themselves. That is why, currently the so-called passive air purification techniques, which include photocatalysis and biofiltration became more and more popular.

4.1. Mechanical ventilation with heat recovery

The traditional way of ventilating rooms in ecological buildings is ineffective because the insulated building envelope and modern window joinery block the infiltration of the outside air and prevent the operation of gravitational ventilation. Therefore, currently the most commonly used technique for refreshing the air in sustainable buildings is a mechanical ventilation system with heat recovery. The air blown into the rooms is pre-purified outdoor air, which is distributed around the building through a ventilation duct system. The air flow forces the fans to work. In addition, in this system there is a possibility of heat recovery from used air. Undoubtedly, a great disadvantage of this solution are high investment and operating costs, which include periodic inspections of the installation, replacement of filters, energy consumption for operation of fans. (Han et al., 2014)

The air filters are the heart of the mechanical ventilation system. These are usually disposable fabric duct filters. Depending on the location in the air transmission system, these can be pre-filters, recirculated and exhaust air.

The primary function of filters is to remove dust from air, i.e. remove solid particles with different aerodynamic diameters. Pre-filters are the least effective, whereas the HEPA and ULPA filters show the highest efficiency.

Pre-filters are used to remove the plant pollen and coarser atmospheric particulate matter and its particles. HEPA and ULPA filters remove fine particulate matter from the air, i.e. PM10, PM2.5 as well as bacteria, fungal spores, and tobacco smoke particles with the efficiency above 99.999%.

In balanced buildings, the dust free air requires additional purification from harmful VOCs, odors, allergens, particulate matter from resuspension as well as ionization or even disinfection. These treatments can be carried out using so-called special filters. Carbon filters are used to remove VOCs and odors, which retain chemical compounds due to the phenomenon of chemisorption. This type of filter is cheap and easy to dispose of after use. In turn, electrostatic filters effectively remove fine particulate matter and can be used to disinfect air. In addition, they can ionize the air negatively, which positively affects the health and well-being of users. Photocatalytic filters are the most advanced type of special filters, which remove fragrances, VOCs and can disinfect air. The frequency of replacement of individual filter sections is different and depends on the degree of contamination of the air being cleaned. It is recommended that this type of filter, with the exception of electrostatic filters, should be serviced for up to 6 months (Liu et al., 2017).

4.2. Potted ornamental plants

Ornamental plants have been a part of the interior of both work and leisure spaces for centuries. Originally, plant arrangements were only meant to improve the aesthetic value of a space. The possibility of using plants to improve the indoor air quality has been the subject of scientific research for only less than four decades. However, their results are so promising that phytoremediation is currently being promoted as a sustainable technique for improving the air quality (Darlington et al., 2010). Moreover, it should be emphasized that in the case of indoor air, the role of plants is not limited to the function of removing impurities, i.e. purification (Horr et al., 2014). Plants also constitute a source of emissions of useful chemical compounds into the air (oxygen, some VOCs), create and regulate elements of thermal comfort (temperature, humidity). They can also be used to support conventional cooling systems in HVAC (Feng et al., 2014; Raji et al., 2015). In addition, phytoncides produced by most plant species can be used for air disinfection. The mechanism of phytoremediation of pollutants from the indoor air is so complicated that it still needs to be clarified as it covers the processes occurring both in the underground (roots) and aboveground (leaves, stems) parts of plants. The effects of specific pollutants on plants have been studied mostly under controlled laboratory conditions: single items, small cubic capacity of the exposure chamber, controlled temperature, RH, controlled concentration of the pollutant. In addition, the experiments were conducted in the absence of additional abiotic and biotic stress. Plants under the real conditions, as living systems, do not act selectively on the individual pollutants but at the same time activate a complex system of phytoremediation. It consists of phytovolitalization and phytofiltration in the leaf zone, phytodegradation and phytoextraction by shoots, as well as rhyzodegradation and rhyzostabilization by root system.

What is known for sure is that the single 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 purifying properties.

VOCs are a serious source of health problems for room users. Safe concentrations of many of these chemicals are regulated only in workplaces. Dangerous 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 phylloosphere 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 during the daytime conditions. Even a long-term exposure of plants to high VOC concentrations did not inhibit their growth (Dela Cruz et al., 2014; Kim et al., 2018; Soreanu et al., 2013). A list of the most recommended plants for VOC remediation from the indoor air is shown in Table 1.

There may be many chemical compounds with oxidizing properties in the indoor air. However, ozone is the most important for plants. In rooms, it can come from both infiltration and arise *in situ*, it is removed mainly through stomata. The speed of the process depends on the plant species (Abbass et al., 2017).

Table 1. Recommended ornamental potted plants for VOC removal from the indoor air

Plant name	Latin name	Pollutants removed
Devil's Ivy	*Epipremnum aureum*	xylene, benzene, formaldehyde, trichloroethylene
Dwarf Date Palm	*Phoenix Roebelenii*	formaldehyde, xylene
Peace Lily	*Spathiphyllum*	benzene, formaldehyde, trichloroethylene, xylene
Philodendron	*Philodendron scandes*	formaldehyde
Spider Plant	*Chlorophytum comosum*	formaldehyde, xylene
Chrysanthemums	*Chrysanthemum morifolium*	ammonia, benzene, formaldehyde, xylene
Rubber plants	*Ficus elastic*	xylene, benzene, formaldehyde, trichloroethylene
Boston Fern	*Nephrolepis exaltata*	formaldehyde and xylene
Areca palms	*Chrysalidocarpus lutescens*	benzene, carbon monoxide, formaldehyde, trichloroethylene, xylene
Dracaena	*Dracaena Deremensis*	xylene, trichloroethylene, and formaldehyde
Ficus/Weeping Fig	*Ficus benjamina*	formaldehyde, trichloroethylene and benzene
Snake Plant/Mother-in-Law's Tongue	*Sansevieria trifasciata*	formaldehyde, trichloroethylene, benzene and xylene
Aloe Vera	*Aloe vera*	formaldehyde
English ivy	*Hedera helix*	formaldehyde and benzene
Flamingo Lily/Fleur	*Anthurium andraeanum*	formaldehyde, ammonia, xylene, toluene
Lady Palm	*Rhapis excelsa*	formaldehyde, ammonia and xylene
Chinese Evergreen	*Aglaonema*	formaldehyde, xylenes
Bamboo Palm	*Chamaedorea seifrizii*	formaldehyde, trichloroethylene and benzene

In many urbanized areas, particulate matter PM10 and smaller fractions are the main air pollutants. Three main pathways can be distinguished by which the PM particles can affect the metabolism of the plant. There are:

- direct deposition on the leaf surface,
- blocking stomata in leaves or being absorbed by leaf tissues,
- deposition on the growing medium of a plant and indirect influence through changes in its chemistry.

The effectiveness of the PM removal by plants is proportional to the mixing of the aerodynamic diameter of dusts and is passive. The mechanism itself has not been fully understood. The key role is played by waxes, which cover the leaf blades. In addition to the dry PM deposition on the leaf surface, the reactions between the particulate matter 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 and Bakera, 2015; Petitt et al., 2017).

The issue of the effectiveness of plants in removing the excess carbon dioxide from the indoor air is still debatable. Some researchers claim that CO_2 assimilation is rather small (Gubb et al., 2018), while others, on the contrary, believe that they reduce the ventilation costs (Tudiwer and Korjenic, 2017). Torpy et al. (2014) indicate 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 and Korjenic, 2017; Irga et al., 2018).

When using houseplants for air purification, determining the effectiveness of the phytoremediation process under real conditions is an important issue. While the results of the tests carried out under model conditions are extremely promising, translating them into the conditions naturally occurring indoors is no longer as spectacular. Model tests are usually carried out on individual plants of a given species under controlled conditions, i.e. temperature, humidity, lighting. Usually, plants are exposed to only one pollutant, which never actually occurs.

Many factors influence the effectiveness of green walls in rooms. If high efficiency of such installations is expected, appropriate conditions for the plant growth should be provided. One of them is lighting. Plants require access to light of the appropriate wavelength and intensity for their growth and maintenance of proper condition. In practice, this involves additional financial expenditure on the implementation of lighting installations because the amount of natural light reaching through the glazed surfaces inside the buildings is definitely too small. Similar requirements apply to the irrigation and fertilization systems.

However, it should be remembered that biophilic installations, with the current state of knowledge, can be rather a support, less often an alternative to the traditional air purification techniques. Hence, it cannot be expected that they will have as high pollutants removal efficiency as conventional mechanical systems.

Green walls perfectly match the principles of sustainable construction. They do not require additional energy to operate, as they are the passive systems. The costs of refreshing treatments for plants with vascular plants are incomparably lower than the periodic air filter replacement in HVAC systems. The plant that needs replacement constitutes green waste that is easy to dispose of. The presence of plants in the immediate vicinity of people positively affects their well-being and has a calming effect. Creating open green space in offices is currently one of the strongest trends in the interior architecture (Moya et al., 2019).

4.3. Photocatalysis

Photocatalysis, according to the IUPAC definition, is a catalytic reaction involving the absorption of light by a photocatalyst or substrate. A photocatalyst is a substance that promotes reactions in the presence of light and is not consumed (Ren et al., 2017). The definition of photocatalysis distinguishes between two main processes. In the first of them, as a result of the radiation of the appropriate wavelength (energy), there is photo-excitation of the catalyst and its interaction with the adsorbed reagent in the basic state – it is so called sensitized photoreaction. However, if the substrates are excited with radiation, which will then interact with the catalyst in the basic state, this is known as catalyzed photoreaction (Lorencik et al., 2016). Heterogeneous photocatalysis, involves examining the interaction processes between a solid state photocatalyst and a liquid or gas phase, containing reagents and reaction products. Photocatalytic degradation processes are a very promising method of removing the inorganic and organic pollutants from the indoor air due to low costs, mild process conditions (temperature and pressure) and the possibility of complete mineralization of pollutants to the main products: CO_2 and H_2O (Nath et al., 2016).

Photocatalytic materials and techniques for air cleaning are based on the principle that the radiation of suitable wavelengths can be absorbed by many semiconductors, which facilitates the creation of reactive oxygen species that can decompose the air pollutants.

TiO_2 is the most commonly used semiconductor with photocatalytic activity. WO_3, ZnO, ZnS, CdS and $SrTiO_3$ are slightly less popular. Anatase is a mineral, which works in the UVA range. In the form of nanoparticles, it is the most photocatalytically active form of TiO_2 in chemical degradation reactions. Currently, many studies aiming to shift the range of actinic radiation towards visible light by TiO_2 doping with different metals are underway (Binas et al, 2017). The efficiency of photocatalytic oxidation of pollutants in the indoor air is affected by: the type and concentration of the pollutant and its affinity for the photocatalyst, chemical interaction and competition among gaseous pollutants, resulting in different rates of photocatalytic degradation, relative humidity, temperature, intensity and wavelength of light source, catalyst poisoning.

In practice, the use of photocatalysis in indoor air purification manifests itself in the use of photocatalytic paints, building materials (concrete, cement, mortar, tiles, glass, silica coatings) and finishing (fabrics) with the addition of TiO_2 and air purifying modules (Huseien et al., 2019). Photocatalytic paints are characterized by the contents of photocatalyst which, when irradiated, favors the oxidation of inorganic (NO_x) and organic gaseous air contaminants (formaldehyde, BTEX). They can also provide self-cleaning activities and show bactericidal properties (Galenda et al., 2018). In terms of appearance and the method of application, they do not differ from traditional the painting products.

Incorporation of TiO_2 into concrete revealed the self-cleaning properties and contributed as green material implementation in engineering constructions.

Photocatalysis has been shown to exhibit the capacity to disinfect the indoor air from a variety of pathogens, including bacteria, fungi, and even some groups of viruses. Photodesinfection can result in one of two outcomes, which are pathogen inactivation due to the cell membrane damage or lysis which refers to the breaking down of the cell integrity.

Purification modules can be installed in portable devices – air purifiers or HVAC systems. Photocatalytic reactor systems can be classified according to their configuration. The most popular types of these appliances are plate, annular, honeycomb monoliths, and fluidized-bed systems. Their efficiency depends on the area coated with photocatalysts, amounts of light sources (UV lamps) and air flow (Zhang and Haghighat, 2015).

One of the limitations of using photocatalysis in air purification is the formation of potential reaction by-products. Most studies on the photocatalytic removal of VOCs and inorganic compounds were conducted in model systems that are very simplified and do not reflect the real conditions. The indoor air is a mixture of hundreds of chemicals that interact with each other. Therefore, under normal operating conditions of photocatalytic devices, the formation of so-called undesirable reaction by-products may occur. They can be formed as either intermediate products or secondary emissions. What is important, some of these photocatalysis by-products might even be more harmful compared to their parent compounds. That is why the formation of such contaminants should be avoided wherever possible. The intermediate products come from the incomplete photocatalysis of certain pollutants. However, secondary emissions are formed due to the photooxidation of the supporting material in which the photocatalysts are embedded.

4. Conclusions

Ensuring proper indoor air quality in residential and public buildings is currently one of the most important problems and challenges faced by architects, builders and sanitary engineers. Public awareness of the effects of breathing polluted air is constantly increasing. This translates into an increase in the demand for technologies that will both clean the air of chemical and biological pollution, but also give it the properties that will create an appropriate indoor climate. Bearing in mind the need to protect the resources of the natural environment, more and more newly constructed or modernized buildings are ecological facilities where, both during their design, construction and, most importantly, exploitation, the demands of sustainable development are met.

Biophilic installations, innovative materials, including photocatalytic, ensure proper indoor air quality. However, it should be remembered that due to certain limitations, their efficiency is not as high as in the case of the conventional air purification systems.

References

1. ABBASS O.A., SAILOR D.J., GALL E.T., 2017, Effectiveness of indoor plants for passive removal of indoor ozone, in *Building and Environment*, 119, p. 62-70.
2. BAUER M., MŐSLE P., SWARZ M., 2010, *Green Building. Guidebook for sustainable architecture,* Springer.
3. BINAS V., VENIERI D., KOTZIAS D., KIRIAKIDIS G., 2017, Modified TiO_2 based photocatalysts for improved air and health, in: *Journal of Materiomics*, 3, p. 3-16.
4. BIELNIAK S., GŁUSZAK M., ZIĘBA M., 2013, *Budownictwo ekologiczne. Aspekty ekonomiczne,* PWN, Warsaw.
5. DARLINGTON A., CHAN M., MALLOCH D., PILGER C., DIXON M.A., 2010, The biofiltration of indoor air: implications for air quality, 2010, in: *Indoor Air*, 10, p. 39-46.
6. DELA CRUZ M., CHRISTENSEN J.H., THOMSEN J.D, MULLER R., 2014, Can ornament potted plants remove volatile organic compounds from indoor air? in: *Environmental Science and Pollution Research*, 21, p. 13909-13928.
7. DUDZIŃSKA M., STASZOWSKA A., POŁEDNIK B., , Preliminary study of effect of furniture and finishing materials on formaldehyde concentration in office rooms, in: *Environmental Protection Engineering*, 35, p. 225-233.
8. FIRLĄG S., 2018, *Zrównoważone budynki biurowe,* PWN, Warsaw.
9. FENG H., HEWAGE K., 2014, Lifecycle assessment of living walls: air purification and energy performance, in: *Journal of Cleaner Production*, 69, p. 91-99.
10. GALENDA A., VISENTIN F., GERBASI R., FANERO M., BERNARDI A., EL HEBRA N., 2018, Evaluation of self-cleaning photocatalytic paints: are they effective under actual indoor lighting systems? in: *Applied Catalysis B: Environmental*, 232, p. 194-204.
11. GAWROŃSKA H., BAKERA B., 2015, Phytoremediation of particulate matter from indoor air by *Chlorophytum comosum L.* plants, in: *Air Quality, Atmosphere & Health*, 8, p.265-272.
12. GUBB C., BLANUSA T., GRIFFITHS A., PFRANG C., 2018, Can houseplants improve indoor air quality by removing CO_2 and increasing relative humidity? *in: Air Quality, Atmosphere & Health*, 11, p. 1191-1201.
13. GUNAWARDENA K., STEEMERS K., 2019, Living walls in indoor environments, in: *Building and Environment*, 148, p. 478-487.
14. HAN K., ZHANG J.S., GUO B., 2014, A novel approach of integrating ventilation and air cleaning for sustainable and healthy office environments, in: *Energy and Buildings*, 76, p. 32-42.
15. HORR Y., ARIF M., KAUSHIK A., MAZROESI A., KATAFYGIOTOU M., ELSARRAG E., 2016, Occupant productivity and office indoor environment quality: a review of the literature, in: *Building and Environment*, 105, p. 369-389.
16. HUSEIEN G.F., SHAH K.W., SAM A.R.M., 2019, Sustainability of nanomaterials based self-healing concrete: an all-inclusive insight, in: *Journal of Building Engineering*, 23, p. 155-171.
17. 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, in: *Reviews of Environmental Science Biotechnology*, 17, p. 395-415.
18. KELLY F.J., FUSSEL J., 2019, Improving indoor air quality, health and performance within environments where people live, travel, learn and work, in: *Atmospheric Environment*, 200, p. 90-109.
19. 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, in: *Horticulture, Environment, and Biotechnology*, 59, p. 143-157.
20. KOTZIAS D., PILIDIS G., 2017, Building design and indoor air quality – experience and prospects, in: *Fresenius Environmental Bulletin*, 26(1), p. 323- 326.
21. LIU G., XIAO M., ZHANG X., et al., 2017, A review of air filtration technologies for sustainable and healthy building ventilation, in: *Sustainable Cities and Society*, 32, p. 375-396.
22. LORENCIK S., YU Q.L., BROUWERS H.J.H, 2016, Photocatalytic coating for indoor air purification: synergetic effect of photocatalyst dosage and silica modification, in: *Chemical Engineering Journal*, 306, p. 942-952.
23. LÓPEZ C.D., CARPIO M., MARTÍN-MORALES M., ZAMORANO M., 2019, A comparative analysis of sustainable building assessment methods, in: *Sustainable Cities and Society*, 49, p.101611.
24. LUENGAS A., BARONA A., HORT C., 2015, A review of indoor air treatment technologies, in: *Reviews in Environmental Science and Biotechnology*, 14, p. 499-522.
25. MASSEY D.D., HABIL M., TANEJA A., 2016, Particles in different indoor microenvironments - its implications on occupants, in: *Building and Environment*, 106, p. 237-244.
26. MARCHWIŃSKI J., ZIELONKA-JUNG K., 2014, *Współczesna architektura proekologiczna*, PWN, Warsaw.

27. MIDOUHAS E., KOKOSI T., FLOURI E., 2018, Outdoor and indoor air quality and cognitive ablility in young children, in: *Environmental Research*, 161, p. 321-328.
28. MORAWSKA L., AYOKO G.A., BAE G.N. et al., 2017, Airborne particles in indoor environment of homes, schools, offices and aged care facilities: the main routes of exposure, in: *Environmental International*, 108, p. 75-83.
29. MOYA T.A., VAN DEN DOBBELSTEEN A., OTTELÉ M., BLUYSSEN P.M., 2019, A review of green systems within the indoor environment, in: *Indoor and Built Environment*, 28(3), p. 298-309.
30. NATH R.K., ZAIN M.F., JAMIL M., 2016, An environment-friendly solution for indoor air purification by using renewable photocatalysts in concrete: a review, in: *Renewable and Sustainable Energy Reviews*, 62, p. 1184-1194.
31. PAWŁOWSKI A., 2011, *Sustainable Development as a Civilizational Revolution, A Multidisciplinary Approach to the Challenges of the 21st Century*, Taylor & Francis Group, CRC Press, Balkema, Boca Raton, London, New York, Leiden.
32. PETTIT T., IRGA P.J., ABDO P., TORPY F.R., 2015, Do the plants in functional green walls contribute to their ability to filter particulate matter? in: *Building and Environment*, 125, p. 299-307.
33. PETTIT T., IRGA P.J., TORPY F.R., *Towards practical indoor air phytoremediation: a review*, Chemosphere, 2018, 208, 960-974.
34. RAJI B., TENPIERIK M.J., VAN DEN DOBBELSTEEN A., 2015, The impact of greening systems on building energy performance: A literature review, in: *Renewable and Sustainable Energy Reviews*, 45, p. 610-623.
35. REN H., KOSHY P., CHEN W.F., SORRELL C.C., 2017, Photocatalytic materials and technologies for air purification, in: *Journal of Hazardous Materials*, 325, p. 340-366.
36. SOREANU G., DIXON M., DARLINGTON A., 2013, Botanical biofiltration of indoor gaseous pollutants – a mini review, in: *Chemical Engineering Journal*, 229, p. 585-594.
37. STEINEMANN A., WARGOCKI P., RISMANCHI B., 112, Ten questions concerning green buildings and indoor air quality, in: *Building and Environment*, 112, p. 351-358.
38. THAM K.W., 2016, Indoor air quality and its effects on humans – a review of challenges and developments in the last 30 years, in: *Energy and Buildings*, 130, p. 637-650.
39. TUDIWER D., KORJENIC A., 2017, The effect of an indoor living wall system on humidity, mould spores and CO_2 concentration, in: *Energy and Buildings*, p. 146, 73-86.
40. UN, 2015, *Sustainable Development Goals*, https://www.un.org/sustainabledevelopment (1.06. 2017).
41. WHO Regional Office for Europe, 2009, *Guidelines for indoor air quality, Dampness and moulds*, Druckpartner Moser.
42. WHO Regional Office for Europe, 2010, *Guidelines for indoor air quality, Selected pollutants*, in puncto druck+medien.
43. ZHONG L., HAGHIGHAT F., 2015., Photocatalytic air cleaners and materials technologies – abilities and limitations, in: *Building and Environment*, 91, p. 191-203.